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THE FORCES OF NATURE.

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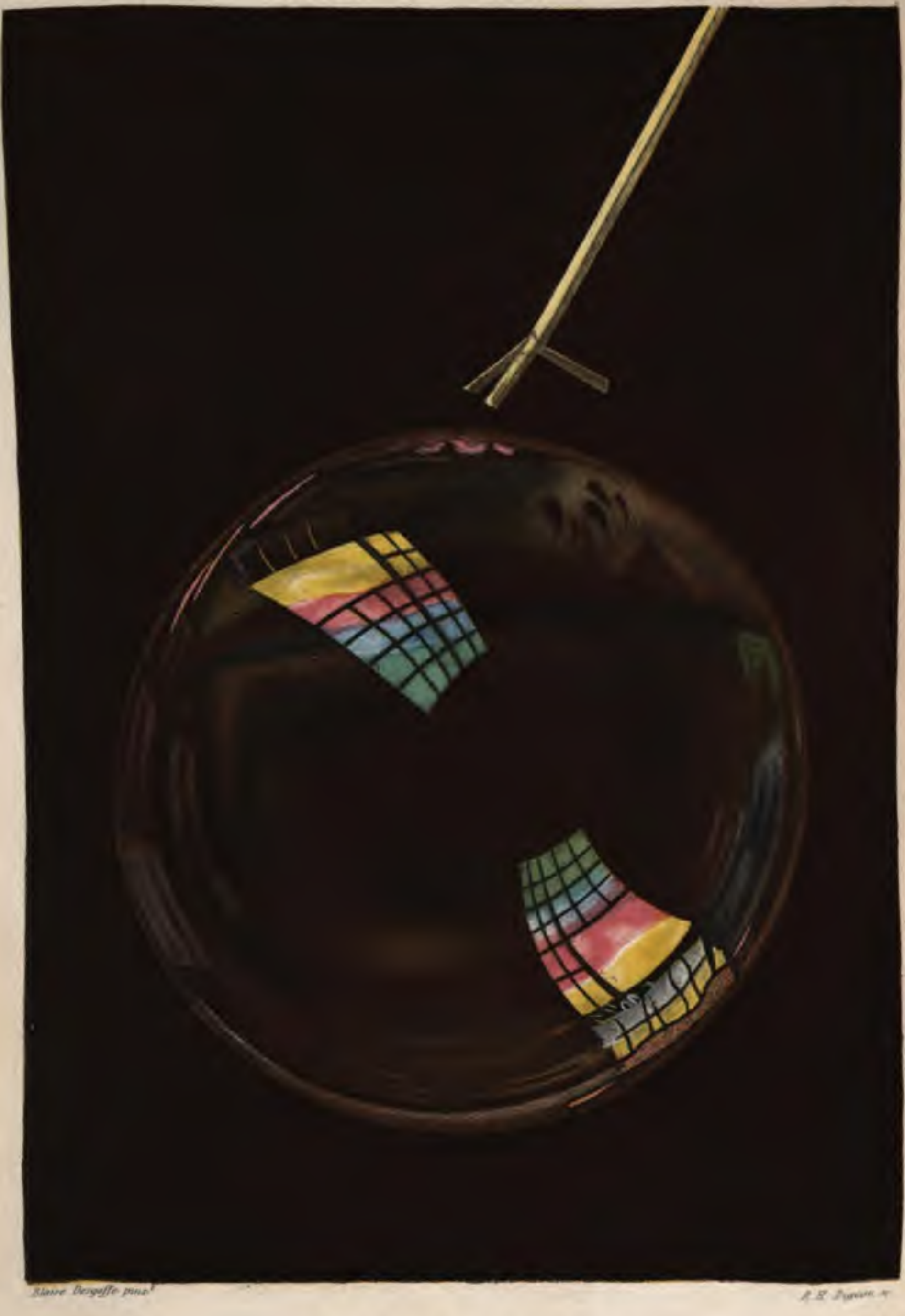

Blaise Desgoffe pinx^t

A.H. Dupuis sc.

SOAP BUBBLE

Interférence Phenomena

COLOURS OF THIN PLATES

THE

FORCES OF NATURE

A POPULAR INTRODUCTION TO THE STUDY OF PHYSICAL PHENOMENA.

BY

AMÉDÉE GUILLEMIN.

TRANSLATED FROM THE FRENCH BY
MRS. NORMAN LOCKYER;

AND EDITED, WITH ADDITIONS AND NOTES, BY
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Illustrated by
ELEVEN COLOURED PLATES AND FOUR HUNDRED AND FIFTY-FIVE WOODCUTS.

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PREFACE.

FROM time immemorial the mind of man has felt a strong desire to fathom the laws which govern the various phenomena of Nature, and to understand her in her most secret work—in short, to make itself master of her forces, in order to render them as useful to material as to intellectual and moral life; such is the noble undertaking to which the greatest minds have devoted themselves. For too long did man wander in this eager and often dangerous pursuit of truth: beginning with fanciful interpretations in his infancy, he by degrees substituted hypothesis for fable; and then, at length, understanding the true method, that of experimental observation, he has been able, after innumerable efforts, to give in imperishable formulæ, the most general idea of the principal phenomena of the physical world.

In order thus to place itself in communion with Nature, our intelligence draws from two springs, both bright and pure, and equally fruitful—Art and Science: but it is by different, we may say even by opposite, methods that these springs at which man may satisfy his thirst for the ideals, which constitute his nobleness and greatness, the love of the beautiful, truth and justice, have been reached. The artist abstains from dulling the brilliancy of his impressions by a cold analysis; the man of science, on the contrary, in presence of Nature, endeavours only to strip off the magnificent and poetical surroundings, to dissect it so to speak, in order to dive into all the hidden secrets; but his enjoyment is not less than that of the artist, when he has succeeded in reconstructing, in its intelligible whole, this world of phenomena of which his power of abstraction has enabled him to investigate the laws.

We must not seek then in the study of physical phenomena, from a purely scientific point of view, the fascination of poetical or picturesque description; on the other hand, such a study is eminently fit to satisfy that invincible tendency of our minds, which urges us on to understand the reason of things—that fatality which dominates us, but which it is possible for us to make use of to the free and legitimate satisfaction of our faculties.

Gravity, Sound, Heat, Electricity, and Light are the divisions under which are arranged the phenomena the description of which forms the object of this work. The programme has not been confined to a simple explanation of the facts: but an attempt has been made to grasp their relative bearings, or, in other words, their laws; a slightly difficult task, perhaps, when we cannot use the clear and simple language of mathematics. It may be added that the present work has been carried out in the same spirit as the astronomical one, "The Heavens;" which is sufficient to show that there has been neither the thought nor the intention to compile a Treatise on Physics; I have been content to smooth the way for those who desire to extend their studies, and likewise to present to general readers a sufficiently exact and just idea of this branch of science.

In this attempt at a description of physical phenomena I have drawn from numerous sources, too long to enumerate, science having developed so much during the last two centuries; but I should fail in a simple act of justice, if I did not express my gratitude to one of our most learned physicists, M. le Roux, who was kind enough to read over most of the proofs of the work, and whose judicious advice has been of so much use to me.

I have also to thank M. Chevreul, who gave me permission to reproduce three plates of his chromatic tints, and M. J. Silbermann, *préparateur* of the course of physics at the Collége de France, who undertook to supervise the reproduction of some of the beautiful pictures in which he has represented several optical phenomena. Lastly, I must acknowledge the valuable aid of the artists, especially MM. Bonnafoux and Laplante, Digeon and Rapine, who have designed or engraved the coloured plates and woodcuts.

AMÉDÉE GUILLEMIN.

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INTRODUCTORY CHAPTER.

FRENCH AND ENGLISH SCIENTIFIC UNITS.

IN the varied examinations into the qualities and properties of matter with which Physical Science is specially concerned, certain units of measurement are essential. And it is unfortunate that in different countries these units are not the same. The Metric or French system, however, is now so universally acknowledged to be the best for scientific purposes, that the Editor by the advice of eminent scientific friends has retained it in this work. Its retention renders necessary a few words by way of introduction.

One great advantage of the Metric System over our own is that it is a decimal system: thus, by the simplest decimal system of multiplication and division, we are enabled to perform with speed and ease any calculations connected with it which may be necessary; another is that the same prefixes are used for measures of length, surface, capacity, and weight; and, finally, these various measures are related to each other in the simplest manner.

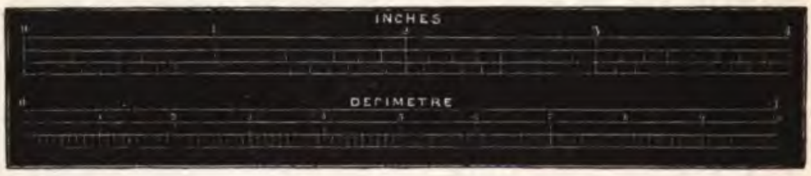
Unit of Length.—The English unit of length is the yard, the length of which has been determined by means of a pendulum, vibrating seconds in the latitude of London, in a vacuum, and at the level of the sea. The length of such a pendulum is to be divided into 3,913,929 parts, and 3,600,000 of these parts are to constitute a yard. The yard is divided into 36 inches, so that the length of the seconds pendulum in London is 39·13929 inches.

The French unit of length, called the *mètre* (from μετρέω, I measure), has been taken as being the ten-millionth part of the quadrant of a meridian passing through Paris; that is to say, the ten-millionth part of the distance between the equator and the pole, measured through Paris. It is equal to 39·3707898 inches. The mètre is divided into one thousand *millimètres,* one hundred *centimètres,* and ten *décimètres;* while a *décamètre* is ten mètres, a *hectomètre* one hundred mètres, a *kilomètre* one thousand mètres, and a *myriomètre* ten thousand mètres. The following table gives the value of these measurements in English inches and yards:—

	In English inches.	In English yards.
Millimètre	0·03937	0·0010936
Centimètre	0·39371	0·0109363
Décimètre	3·93708	0·1093633
MÈTRE	39·37079	1·0936331
Décamètre	393·70790	10·9363310
Hectomètre	3937·07900	109·3633100
Kilomètre	39370·79000	1093·6331000
Myriomètre	393707·90000	10936·3310000

One English yard is equal to 0·91438 mètre; while one mile is equal to 1·60931 kilomètre.

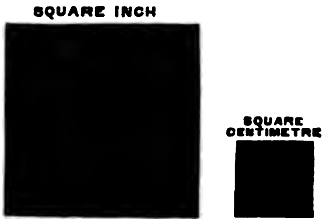
In the annexed woodcut a décimètre, with its divisions into centimètres and millimètres, is shown, and compared with four inches divided into eighths and tenths.



Unit of Surface.—For the unit of surface, the square inch, foot, and yard adopted in this country are replaced in the metric system by the square millimètre, centimètre, décimètre, and mètre.

1 square mètre = 1·1960333 square yards.
1 square inch = 6·4513669 square centimètres.
1 square foot = 9·2899683 square décimètres.
1 square yard = 0·83609715 square mètre.

In the annexed woodcut a square inch and a square centimètre are shown, in order to give an idea of measures of surface which will often be referred to in the following pages.



Unit of Capacity.—The cubic inch, foot, and yard furnish measures of capacity; but irregular measures, such as the pint and gallon, are also used in this country. The gallon contains ten pounds avoirdupois weight of distilled water at 62° F.; the pint is one-eighth part of a gallon. The French unit of capacity is the *cubic décimètre* or *litre* (λίτρα, the name of a Greek standard of quantity), equal to 1·7607 English pints, or 0·2200 English gallon; and we have cubic inches, décimètres, centimètres, and millimètres.

1 litre = 61·027052 cubic inches.
1 cubic foot = 28·315311 litres.
1 cubic inch = 16·386175 cubic centimètres.
1 gallon = 4·543457 litres.

Unit of Mass or Weight.—The English unit of weight—the pound—is derived from the standard gallon, which contains 277·274 cubic inches; the weight of one-tenth of this is the pound avoirdupois, which is divided into 7,000 grains. The French measures of weight are derived at once from the measures of capacity, by taking the weight of cubic millimètres, centimètres, décimètres, or mètres of water at its maximum density, that is at 4° C. A cubic mètre of water is a tonne, a cubic décimètre a kilogramme, a cubic centimètre a gramme, and a cubic millimètre a milligramme.

	In English grains.	In lb. Avoirdupois. 1 lb. = 700 grammes.
Milligramme ($\frac{1}{1000}$th part of a gramme)	0·015432	0·0000022
Centigramme ($\frac{1}{100}$th „ „)	0·154323	0·0000220
Décigramme ($\frac{1}{10}$th „ „)	1·543235	0·0002205
GRAMME	15·432349	0·0022046
Décagramme (10 grammes) . . .	154·323488	0·0220462
Hectogramme (100 „) . . .	1543·234880	0·2204621
Kilogramme (1000 „) . . .	15432·348800	2·2046213
Myriogramme (10000 „) . . .	154323·488000	22·0462126

Besides these units, there are others on which a few words may be said, as the units before referred to are implicated. The *Unit of Time or Duration* is the same for all civilized countries. The twenty-fourth part of a mean solar day is called an hour, and this contains sixty minutes, each of which is divided into sixty seconds. The *second* is universally used as the unit of duration.

Having now units of space and time, we are in a position to fix upon a *Unit of Velocity.*—The units of velocity adopted by different scientific writers vary somewhat; the most usual, perhaps, in regard to sound, falling bodies, projectiles, &c., is the velocity of feet or mètres per second. In the case of light and electricity, miles or kilomètres per second are employed.

We have next the *Unit of Mechanical Work.*—In this country the unit of mechanical work is usually the *foot-pound,* viz. the force necessary to raise one pound weight one foot above the earth in opposition to the force of gravity. A *horse-power* is equal to 33,000 lb. raised to a height of one foot in one minute of time. In France the *kilogrammètre* is the unit of work, and is the force necessary to raise one kilogramme to a height of one mètre against the force of gravity. One kilogrammètre = 7·233 foot-pounds. The *cheval-vapeur* is nearly equal to the English horse-power, and is equivalent to 32,500 lb. raised to a height of one foot in one minute of time. The force competent to produce a velocity of one mètre in one second, in a mass of one gramme, is sometimes adopted as a unit of force.

Unit of Heat.—These units vary: the French unit of heat, called a *calorie,* is the amount of heat necessary to raise one kilogramme (2·2046215 lb.) of water one degree Centigrade in temperature; strictly from 0° C. to 1° C. In this country we sometimes take one pound of water and 1° Fahrenheit as the units; sometimes one pound of water and 1° C.

Thermometric degrees.—The value of different thermometric degrees is discussed in the work itself (*vide* Heat, Book IV., chapter i.). The following facts may be found useful:—

1° Fahrenheit = 0·55° C. = 0·44° R.
1° Centigrade = 0·80° R. = 1·80° F.
1° Réaumur = 1·25° C. = 2·25° F.

Centigrade degrees ÷ 5 × 9 + 32 = Fahrenheit degrees.
Réaumur „ ÷ 4 × 9 + 32 = „ „
Fahrenheit „ − 32 ÷ 9 × 5 = Centigrade „
„ „ − 32 ÷ 9 × 4 = Réaumur „
Centigrade „ ÷ 5 × 4 = „ „
Réaumur „ ÷ 4 × 5 = Centigrade „

BOOK I.

GRAVITY.

PHYSICAL PHENOMENA.

BOOK I.

GRAVITY.

CHAPTER I.

PHENOMENA OF GRAVITY ON THE SURFACE OF THE EARTH.

Manifestation of weight by motion : fall of bodies, flowing of liquids, ascent of gas—Pressure of bodies in equilibrium ; stability of the various solid, liquid, and gaseous strata which constitute the terrestrial globe—Crumbling away of mountains ; fall of avalanches and of blocks of ice in the polar regions—Air and sea currents.

A STONE left to itself in the air falls, and its movement is arrested only on touching the ground ; a round body, or a solid ball, rolls along a plane inclined to the horizon ; a liquid mass, such as a brook or large river, flows on the sloping surface which forms its bed; smoke and steam rise into the air. All these phenomena, and many others that we shall review, are the varied manifestations of one ever-active force, universally distributed throughout all nature, which is called *Weight.*

All bodies, without exception, which are found on the surface of our planet—in the depths of its crust, or in the gaseous strata of which its atmosphere is formed—have weight. This is a fact so obvious that in the case of solid and liquid bodies it hardly requires to be stated. We shall soon have occasion to show that it holds good also with regard to gases and vapours.

Nor is it only moving phenomena which familiarize us with the action of weight: it exercises itself also incessantly on bodies which appear to us to be at rest, and which in reality are only in equilibrium. The stone which has touched the ground, the fall of which our èyes have followed, continues thenceforth to weigh on the surface which upholds it, and this pressure, which is rendered evident by the constant tension of a spring (Fig. 1), is rendered sensitive to our organs by the effort which the hand is obliged to use to support the stone.

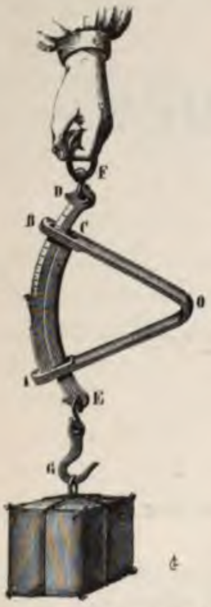


Fig. 1.—Action of weight shown by the tension of a spring.

A book placed on the table remains at rest, but presses on its support, which itself rests on the ground. A mass of metal suspended at the lower end of a thread or flexible cord stretches the thread or cord; this tension, which continues as long as the suspending thread is not cut, proves the continuous action of the force on the suspended body.

We must therefore clearly understand that rest is not synonymous with inaction, and we may be assured that, on the earth, no material particle, whether solid, liquid, or gaseous, is ever for one moment free from the action of this force.

Let us now endeavour to give a general picture of the terrestrial phenomena—phenomena of equilibrium and of motion—which are produced by this force.

Astronomy teaches us that the earth is of the form of a nearly spherical ball, and has two movements—movements in which all the parts of its mass participate at the same time: one of uniform rotation round one of its diameters, the other of translation, which draws it with varying velocity along an elliptic orbit, the sun being in a focus of that orbit. But neither the one nor the other of these movements directly affects the equilibrium of its various parts. The solid masses which form its crust; the nucleus, probably in a state of incandescent fusion, which forms the interior; the liquid part of its surface, the oceans; and lastly, the gaseous envelope which surrounds every portion of the spheroid, are in a state of relative stability, resulting from mutual pressure, due to the force which is now in question.

It appears certain that the entire earth was once fluid, and that the different strata of which its interior is formed have ranged themselves in the order of their densities—that is to say, the heaviest at the centre, the lightest at the surface, according to the same conditions which experience has proved to be necessary to the stability of liquids and to their equilibrium under the action of weight. And—to speak only of the parts accessible to observation —it is seen that such is precisely the order of their succession. Below we have the solid crust—the solid surface of the earth: afterwards comes, spread over three quarters of this surface, the liquid part or sea: then above both, the gaseous strata which form the atmosphere. Of these different constituents, the air presses on the water, and both press on the solid ground.

Let us examine the surface of the continents and islands. We find everywhere that the relief of the ground is such that all its parts mutually support each other. In the mountains, as in the plains, weight acting on each particle has arranged the masses in such a way that equilibrium is never or very rarely destroyed. Suppose the action of weight suppressed; the other physical forces, no longer finding resistance, would overturn the fields, rocks, and mountains, and would everywhere substitute disorder and confusion in place of the order which results from their present stability. It is again the pressure due to weight which man utilizes when he builds his most durable constructions in imitation of nature. The mass of the materials, their vertical disposition, or, better still, their slope, as in the case of the Pyramids of Egypt, have enabled some of the monuments constructed by man to defy the action of the elements and of centuries. We shall have occasion to notice in the second part of this work other applications of the action of weight to the arts and various industries. Let us here only remark, as an instance of this, that we look to it to produce adherence of the smooth wheels of locomotives to the rails: it is the enormous weight of the engines which prevents their driving-wheels from continually revolving without making any progress; and it is not a little curious that, in the infancy of the locomotive, the result of the pressure on the rail due to the weight of the engine was so little understood, that it was thought that cogged wheels instead of smooth ones would be necessary.

It is their weight also which keeps the waters of rivers in their natural beds, and lakes and seas in their basins, where these masses would remain at rest if exterior forces did not perpetually arise to agitate them. It happens sometimes that, under the influence of causes of irregular and terrestrial origin,—such as earthquakes and winds, to which may be added the periodical oscillations of the tides,—the sea is upheaved to great heights, and breaks beyond its usual limits. But it is soon drawn back to its more common state of equilibrium, either by its own weight or by friction—another cause of stability, the origin of which is also weight. Laplace, as the result of an inquiry into what were the conditions necessary to the absolute stability of the equilibrium of seas, proved that it is sufficient that the density of the ocean be less than that of the earth—a condition which is precisely realized in nature. Thus, if they were lighter, the waters of the sea would be in a perpetual state of mobility; if they were heavier, the variations from a state of equilibrium owing to accidental causes would be considerable, and would occasion frightful catastrophes both on continents and islands.

But the persistence of the action of weight is not observable only in the land and water masses: the air is also subject to it. Without this pressure, which keeps them to the earth's surface, the elasticity, or the force of expansion, which is, as we shall soon see, a distinctive property of gases, joined to the centrifugal force due to the rotation of the earth, would soon dissipate the atmosphere into space.

Such are, as a whole, the phenomena due to the continuous and latent action, so to speak, of weight on our globe. It is this action which everywhere maintains equilibrium, and which re-establishes it when it is disturbed by the action of physical forces.

The phenomena of motion, due to the same force, form an equally interesting and magnificent picture. The infiltration of the waters through the earth's surface to different depths is due to this irresistible tendency of all bodies towards the centre of the earth. It is this tendency which by degrees undermines the land and rocks, and, disturbing their equilibrium, gives rise to the falling away of the sides of mountains and hills, and in time fills up the valleys. These movements have not the action of weight only for their origin, and we shall see further on how this action combines itself with those of other physical or chemical forces, and particularly with that of heat, to cause most of the motion of which the surface of our globe and its atmosphere are the constant scene.

Often the work of disorganization remains unperceived until the instant when the catastrophe occurs. Masses of high rocks being undermined, all at once lose their equilibrium, and slide or are dashed down, destroying everything in their path. Entire mountains have thus covered towns and villages with their *débris*, and history has recorded numerous examples of these terrible events. In the thirteenth century, Mount Grenier, the summit of which still towers above the mountains which border the Valley of Chambéry on the south, partly crumbled away, and buried the little town of Saint-André and many villages: the "*abîmes de Myans*" are still shown, where lie the *débris* and the victims. In 1806 a no less terrible landslip took place, and precipitated from the sides of Mount Ruffi, into the Valley of Goldau, an enormous mass of rock, which completely buried many villages, and partly filled up a little neighbouring lake.

It would be superfluous to calculate what is the destructive energy of similar masses precipitated by the action of weight from a height often prodigious, and the velocity of which increases with the height of the fall. Avalanches are phenomena of the same order, and are more frequent than the fall of mountain-sides and rocks. Masses of snow, collected on the inclined side of a mountain, or on the edge of a precipice, slide by their own weight, then detach themselves, and fall, crushing everything in their path. Often a slight shock—a pistol-shot, or a shout even—is sufficient to destroy the equilibrium, and occasion the phenomenon. In the icebergs, or mountains of ice in the polar regions, the pressure of the blocks one upon the other gives rise to similar effects, in which the irresistible action of weight again shows its power. Glaciers, too—those rivers of hardened snow pressed into compact ice—descend the slopes of the mountains under the pressure of the weight of the upper strata. This movement of slow progression is so irresistible, that the lateral and underlying rocks are striated and polished by the crystalline mass, and by the *debris* of boulders and pebbles which it draws along.

In volcanic eruptions, the explosive force of the interior gases often sends forth into the air cinders, fragments of stone, and rocks. But if these masses thus seem to escape for a moment from the action of gravity, the strife of the two forces is not of long duration, and the projectiles obey the invincible law of all terrestrial bodies. It is this same law which determines the fall of hail, rain, snow—that is to say, the particles of aqueous vapour which have been condensed, and thus rendered heavier than the stratum of the air to which they rose, under the combined influence of heat and even—paradoxical as it may seem—of weight itself.

Thus much, then, concerning the fall, properly so called, of bodies of which the equilibrium, from some cause or other, has been disturbed. But there is, on the surface of our planet, quite another series of movements, in which weight plays the most important part, and the continuity of which produces an admirable circulation on our planet, without which life itself would soon be extinct.

The incessant evaporation of liquid masses gives rise to the formation of clouds, and it is the difference between the weight of the air, and of the particles of vapour of which clouds are formed, which causes their ascending movement. Rain, due to the fall of these same particles when liquefied, falls through the action of terrestrial gravity, to the lowest levels—forms brooks and rivers, and these fluvial masses following the natural slope of the ground, reach the sea, sometimes flowing with majestic slowness, at other times rushing noisily over a rugged bed. Sometimes, stopped by natural obstacles, the waters spread themselves in the form of lakes: or else, arriving at the edge of a wall of rocks, flow over in cascades. Such are the falls of the Rhine at Schaffhausen, of Niagara, and the Zambesi cataracts in Central Africa.

Currents are not peculiar to the solid portion of the surface of the earth. The ocean is furrowed with real rivers, the regular movements of which are determined by the action of weight, although their origin is due to another physical agent—heat. It is also weight which regulates all the movements of the atmospheric gaseous mass, which unites its restless power to the action of the other natural forces.

In conclusion, there is no action on our planet in which weight does not intervene sometimes to establish equilibrium, at others to give rise to motion. Even when it appears to be destroyed or counterbalanced, it is still at work, and is ever present wherever a particle is found, apparently invariable, and, according to the ideas experiment has given us of matter, as indestructible and eternal as matter itself.

CHAPTER II.

WEIGHT AND UNIVERSAL GRAVITATION.

Common tendency of heavy bodies to fall towards the centre of the earth—Weight is a particular case of the force of universal gravitation—All the particles of the globe act on a falling stone as if they were all situated in the centre of the earth—The force of gravity acts beyond the atmosphere even in the celestial spaces: the sun, planets, stars—all bodies—gravitate towards each other.

ALL the varied and numerous phenomena to which we referred in the previous chapter have the same origin—a fact which will become more evident as experimental proofs are given. All are due to the action of a similar cause, or *force*, since this term is now given to every cause capable of producing or of modifying motion in a body as of bringing it back to a state of rest.

What the essence or primordial cause of this force is, is a problem which science does not seek to solve: it confines itself to studying the effects of the force by means of observation, and thence to discover the law which regulates them; and in this we shall soon see it has completely succeeded. The direction of the action of weight, that is to say, the line in which the heavy body tends to move or is moved when it meets with no resistance; the point at which the force is applied; and, lastly, its intensity or the energy with which it attracts or pulls each material particle, are facts exactly determined. We shall recur in detail to them in the following chapters.

We know by experiment that a force resides somewhere, that it has its centre of action in a given place. We may say more: we cannot conceive it acting without a material body to act upon. Where, then, is the centre of action of terrestrial gravity? It is not in the heavy body itself. Indeed, according to a principle of paramount importance in the science of motion, or *dynamics*—the principle of *inertia*—a body cannot put itself in motion when it is at rest, nor of itself modify its movement when in motion.

It is, then, outside a falling body that we must look for the cause of its fall. We are so accustomed, from our infancy, to see all bodies which surround us falling under the action of weight, or in other words to see the force of gravity at work, that the question seems to be an idle one. But, as D'Alembert has said, "It is not without reason that philosophers are astonished to see a stone fall, and those who laugh at their astonishment would soon share it themselves, if they would reflect on the question."

It is from above downwards, in the vertical of any place—that is to say, in a line upright or perpendicular with regard to the surface—that all bodies fall, and it is in the same direction that they press on their supports. Weight, then, we see, acts as it were from the interior of the earth; and since for points at short distances apart, the verticals, or upright lines, at these points seem parallel, it may be supposed that, instead of a single force, there exists an infinity of forces, all acting in the same manner and in the same direction. But it is easily seen that this last conclusion is not exact.

Weight, or gravity, everywhere acts in the same manner. In all places, in all latitudes, at the equator, at the poles, in the temperate regions of the world, its influence is felt always in a direction perpendicular to the horizon. To know at what point of our globe this multiple action is concentrated, we must find out if all the verticals have a single common meeting-place. Let us take any one of the meridians of our planet. Each part of the circle which forms the meridian indicates an horizon, and the line perpendicular to this, or the vertical of the place, is no other than one of the radii of the circumference; that is to say, a line running to the centre of the

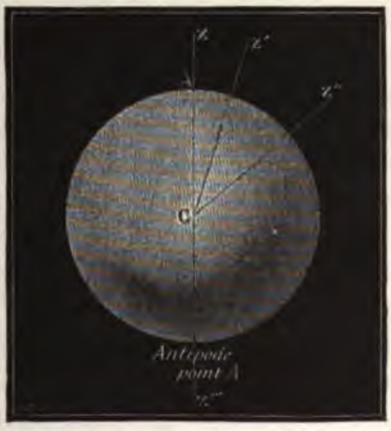


FIG. 2.—Convergence of the verticals towards the centre of the earth.

sphere. Thus all verticals, such as A Z, Fig. 2, though apparently parallel when adjacent ones only are considered, are in reality convergent; they are directed towards the centre, C, of the earth. This is only a first approximation: the earth not being exactly spherical, but flattened at the poles and swelled out all round its equatorial circumference, the verticals of the different latitudes do not precisely tend to the same point. We shall observe also that besides this cause of deviation there exist local irregularities which render the determination of the real centre of the action of gravity very complex. But from our present point of view these different deviations have no importance. Let us now register this first fundamental result:

All bodies have a tendency to fall towards the centre of the earth. Gravity acts on them, as a single force concentrated in this point.

This law has no exception. It applies to bodies placed on the surface or at any height whatever in the atmosphere; on the earth's crust, or in the deepest mines, observation always confirms its truth.

This convergence of all falling bodies which tend towards one point, is in contradiction with a popular prejudice still prevalent. Many persons when they are told that the earth is round, and that it is inhabited on every part of its surface, cannot conceive how at their antipodes the inhabitants of the planet can walk, as it were, *feet uppermost*, and how material bodies, solid or liquid, can remain in equilibrium. By reflecting a little they would soon see that the idea of above and below is quite relative; that on a sphere in space each part of the surface is equally horizontal, and the tendency of all bodies towards the centre of the sphere well explains the state of equilibrium which exists on whatever part of the surface they are placed.

But whence comes this central force? Is it a secret property independent of matter? Does the earth alone enjoy this mysterious power?

These important questions remained unanswered two centuries ago, since which time Galileo's experiments on falling bodies, and the profound speculations of Huyghens on the principles of mechanics, enabled the genius of Newton to reach the general cause which produces all the phenomena of gravity on the surface of the earth as well as throughout the entire universe. Weight is, in fact, a particular case of a force at work in all parts of the universe—the force of universal gravitation. In virtue of this force, any two particles of matter gravitate or fall towards each other, that is to say, they have a mutual tendency to re-unite, which depends on their respective masses and on their distance apart. Here is the law of this dependence:—

If we take for unity the force which draws two equal masses, situated at a unit of distance apart, towards each other, if one of the masses be doubled, the force itself will be doubled: if the other mass be replaced by one three times greater, the force will be now tripled, and, in consequence, will be six times greater than at the beginning.

If now, the masses remaining the same, we make the distance twice, three times, four times *less*, the force of gravitation will be four, nine, sixteen times *greater*.

Thus, attraction, or gravitation—we shall use this latter term in preference (discarding altogether in future the term weight, which by this time should have served its purpose), because it supposes nothing as to the unknown essence of the force itself—*is proportional to the product of the masses, and varies inversely as the square*[1] *of their distances.*

Such is the fundamental principle of which the phenomena of weight are so many particular manifestations. It was not an easy thing to deduce from it all the consequences, to calculate the reciprocal actions of all the small masses composing the entire bulk of the earth, and the effect resulting from all these combined actions. Newton, and after him the great geometers who have developed his discovery, D'Alembert, Euler, Maclaurin, Lagrange and Laplace, have devoted themselves to this task. They have shown that a spherical mass of homogeneous matter acts on an exterior point in the same way as if all the matter were concentrated at its centre. The same thing is true of a homogeneous spherical layer, and consequently of a series of strata of this same form, the density of which continues to increase according to a definite law.

Such is precisely the case with the earth: and Newton thus explains how the direction of gravity is everywhere vertical to the surface, or the straight line between the heavy body and the centre of the globe.

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[1] The square of a number is the product of the multiplication of the number by itself: thus 9 is the square of 3; 100, the square of 10; 1,000,000 the square of 1,000, and so on.

A body situated in the interior of the earth is attracted by the mass which lies beneath it, but the action of the particles of the exterior layer destroy each other, so that the intensity of gravitation goes on diminishing from the surface to the centre.[1] In like manner, this intensity diminishes in the case of bodies exterior to the earth, in proportion as their distance from the earth increases.

Thus, then, the source of gravity at the surface of our globe lies in the entire mass of which it is composed. There is not a single particle, however small it may be, which does not take part in the general action. Nay, more: when a stone falls, at the same time that it feels the influence of the mass of the globe it reacts on this globe by its own bulk: the two bodies come together by gravitating one towards the other. The motion of the stone, however, is alone perceptible, as its mass is almost nothing compared to that of the earth. But more of this presently.

It has been stated that gravitation is universal. Not only, indeed, does it govern all the phenomena of terrestrial gravity, but it extends its power to the most remote parts of the heavens. The moon and the earth gravitate reciprocally towards each other, and they both gravitate towards the sun. All the planets of our solar system continually act on one another, and on the immense sphere which shines at their common focus. By its enormous mass, the sun keeps all of them in their orbits, so that the movements of all the celestial bodies which compose the system are mutually balanced and varied under the influence of the same force perpetually acting in each of them.

We have endeavoured to give elsewhere[2] an idea of these grand problems, the solution of which is the triumph of science. Let us recall only two proofs of the existence of the force of universal gravitation in the celestial spaces. The tides—those periodical oscillations of the sea—are produced by the action of the masses of the moon and sun: and aërolites, celestial bodies in miniature, which sometimes fall on our planet, show that the action of terrestrial gravity is capable of diverting exterior masses from their orbits.

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[1] In fact, the intensity of gravity first increases from the surface to a distance from the centre which is estimated at nearly seven-tenths of the radius; it afterwards lessens to the centre. These variations are due to this fact, that the concentric layers of which our globe is formed are not homogeneous; their density increases from the surface to the centre, and the density of the superficial strata is less than two-thirds of the mean density. These results have been deduced from pendulum observations.

[2] "The Heavens: an illustrated Handbook of Popular Astronomy." By A. Guillemin. Translated by Mrs. Lockyer.

The most recent researches in stellar astronomy prove, moreover, that the same force regulates the movements of the most distant stars. The double stars are systems of suns, situated at immense distances from our globe, and revolving round each other: here, again, it is certain that their motions are effected according to the same laws which regulate those of the planets—laws which are a direct consequence of gravitation, that is, of their weight.

CHAPTER III.

LAWS OF ATTRACTION.—FALLING BODIES.

First experiments of Galileo on falling bodies—Equal velocity of bodies falling *in vacuo*—Vertical direction of gravity—Deviation from the vertical due to the rotation of the earth—Galileo's inclined plane; Attwood's machine; Morin's machine: laws of falling bodies—Influence of the resistance of the air on the velocity of bodies falling through the atmosphere; experiments of Désagulier.

IT is recorded of Galileo that in his youth, when he was Professor of Mathematics at the University of Pisa, making his first experiments on the fall of heavy bodies, he wished to see if it were true, as had been said and believed from the time of Aristotle, that the unequal velocity noticed in different bodies falling from a given height was due to their unequal weight, or if it depended on the nature of their material.

It was from the top of the famous Leaning Tower of Pisa that he made these experiments: balls of different metals—gold, copper, lead—having the same dimensions, but different weights, reached the ground at nearly the same instant: a ball of wax, however, was much more retarded.

But the differences in the times of falling were not decided enough to be attributed to the inequality of weight, so that it did not appear probable that, as held by many, a thing twice as heavy as another would fall twice as fast.

Having let the same thing fall through the air and through water, he proved that the differences between the times of their respective falls depended upon the density of the medium through which they fell, and not on the weights of the falling bodies themselves. Galileo hence concluded that it is to the resistance of the air we must attribute the differences in the time of fall observed.

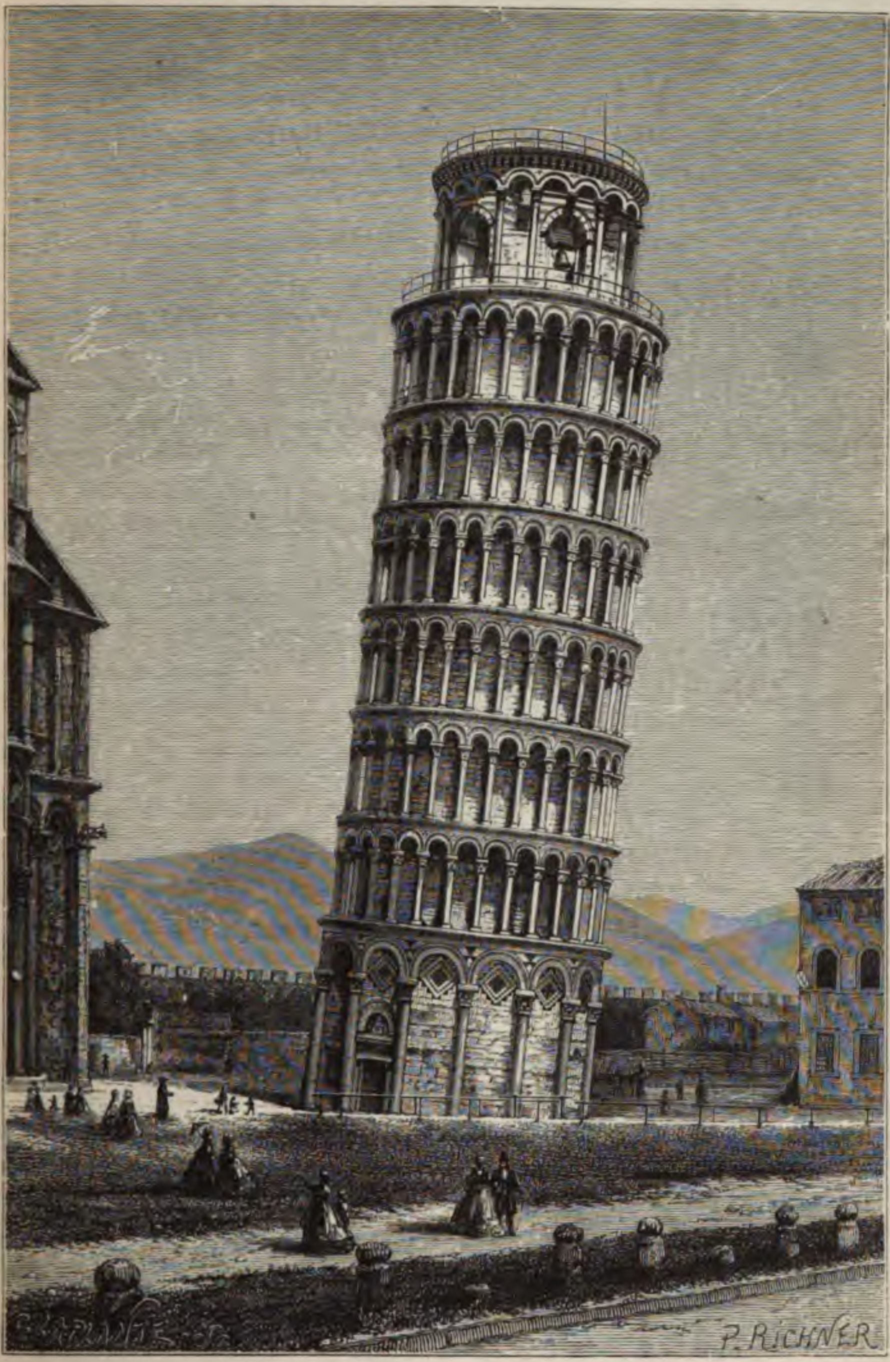

FIG. 3.—The Leaning Tower at Pisa.

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When a body falls through air, or any other medium, it must constantly displace the molecules of which the medium is composed, and this is only possible by communicating to them a part of its own movement. Suppose, then, we let fall at the same instant a ball of lead and a ball of cork of equal weight: the latter loses more of its own movement than the first does in displacing the same quantity of air, because being of a lighter substance it is larger, so that its speed is naturally more diminished. The difference would be still more perceptible if the fall, instead of being effected through the air, were to take place in a dense gas.

Galileo's discovery has since been exactly confirmed by experiment, and the honour of this confirmation belongs to Newton.

Take a long glass tube furnished at both ends with two frames of copper, one hermetically closed, the other terminated by a stopcock, which allows the tube to be adjusted on the table of an air-pump, an instrument by which we can carry off, or exhaust, the air which it contains. We now introduce into one end of the tube bodies of different densities, such as small pieces of wood, metal, feathers, paper, cork, &c. After exhausting the air by means of the air-pump, and turning the stopcock to prevent its re-entrance, we turn the tube quickly, and place it in a vertical position. All the little bodies at once quit the top and fall together in the direction of the axis of the cylinder (Fig. 4). If the tube be inverted before the air is extracted, the unequal rate of fall is clearly shown. If the experiment be repeated several times, gradually letting the air into the tube, it will be observed that this inequality decreases with the rarefaction of the air in the tube. When the vacuum is as complete as possible, all the bodies, although of different densities, reach the lower part of the instrument at the same time.

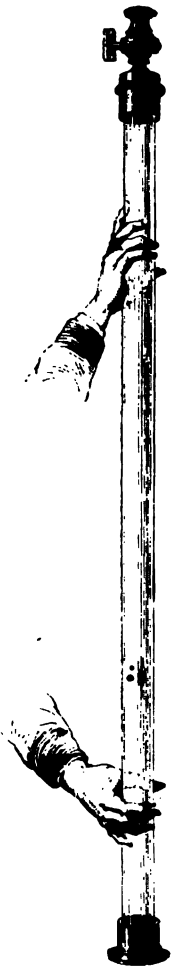
FIG. 4. — Experiment showing the equal velocity of bodies falling *in vacuo*.

It is then the resistance of the medium which is the cause of the thread is called a plumb-line or plummet, and is used by workmen who wish to construct an upright building. Placing the plumb-line above a liquid mass at rest, for example a mercury bath, it is easily seen that the direction of the string and that of its image are in the same straight line (Fig. 5), and consequently, in virtue of the laws of the reflection of light, which we shall discuss in the sequel, both are perpendicular to the horizontal surface of the liquid.

The different verticals, we have already said, are not parallel; but at very slight distances the angle which they form is so small that it is impossible to measure it. This is not the case if we take two places on the earth somewhat distant from each other: in this case their respective verticals can be measured by means of astronomical observations. If the two places are on the same meridian, and have the same geographical longitude, the angle of the verticals is measured by the difference of latitude. The difference between the directions of gravity between Paris and Dunkirk is thus found to be about 2° 12′, between London and Edinburgh about 4° 25′; the vertical which passes through the top of the cross of St. Paul's and that which passes through the flagstaff on Victoria Tower make but a very small angle with each other.[1]

Hence it follows that the waters of a lake or of a sea are bounded by a surface which is not plane, but spherical, or rather spheroidal, although at every part or point of the earth's surface it is confounded with the plane of the horizon of the place.

We must therefore understand that when it is said that heavy bodies fall in a constant direction, which is that of the vertical of the place, this constancy implies only a parallelism of fall at places very near together.

Lastly, let us add that the rotatory movement of the earth produces a deviation in the fall of bodies. A body at *a* (Fig. 6), situated at a certain height in the air, would fall at the foot of the vertical at A, if the earth was immoveable. But during the time of its fall, the rotatory movement makes it describe an arc *a a'*, larger than the arc A A' described by the base of the vertical. Left to itself, it retains its velocity of primitive impulsion, and ought to fall at A to the east of the lower point. Such is the deviation which the theory indicates, and which, being nothing at the poles, goes on increasing towards the equator. Experiment confirms the reasoning: in the atmosphere, however, it is difficult to succeed in the experiment, on account of the disturbances in the air; but it can be proved that a metallic ball A dropped at the mouth of a very deep mine, falls at B', a little to the east of the foot B of the plumb-line which marks the vertical. The deviation depends of course on the depth of the mine: at the equator it is 33 millimetres for a well 100 metres deep. For a mine at Freiburg, in Saxony, M. Reich proved an eastern deviation of 28 millimetres at a depth of 158·5 metres, theory indicating 26·6 millimetres. It is evident, then, that we have here an experimental proof of the earth's rotation.

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[1] If the experiment is made in the neighbourhood of a very high mountain, the plumb-line is deflected from the vertical, under the influence of the attraction of the mass of the mountain. This deviation, always very slight, was first measured by Bouguer and Lacondamine, on the side of the Chimborazo. In 1774 Dr. Maskelyne measured the attractive influence of Mount Schihallion, which he found equal to about 12″; that is, two plumb-lines, situated on either side of the mountain, instead of forming between them the angle indicated by the difference of latitude of the stations, formed one larger by 12 seconds.

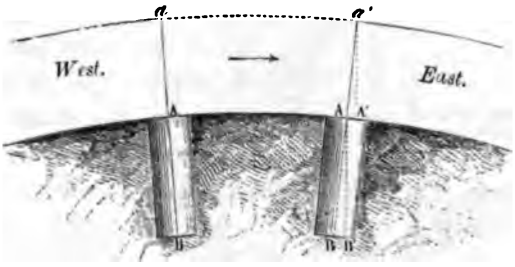

FIG. 6.—Eastern deviation in the fall of bodies.

Galileo, in his experiments on the fall of heavy bodies, did not confine himself to destroying the popular fallacy, which was still prevalent in his time, regarding the inequality of the velocity of fall being attributable to the difference of weight or to the density of the substances. He observed that the velocity acquired increased with the heights of the fall; that the spaces traversed were not simply proportional to the times employed to traverse them,—in fact, that the fall of heavy bodies, instead of being a uniform, is an accelerated movement. Such an assertion doubtless had been made before him.

but he had the glory of discovering the precise law of variation of the velocity acquired and the space described. Supposing that gravity, whatever its essence might be, acted always with the same force, he concluded that the velocity acquired ought to be proportional to the time, and he proved his hypothesis by a celebrated experiment, to which his name has remained attached. This was the inclined plane of Galileo. The rapidity with which heavy bodies, metallic balls for instance, travel in their fall, does not easily allow of direct observation. But Galileo knew that a heavy body left to itself on a plane inclined to the horizon, and subjected only to the action of gravity, follows in its movements the same laws as if it fell vertically; the friction of the body on the plane and the resistance of the air during the fall, in the two cases being disregarded. The force which draws the body down the inclined plane is no other than gravity, diminished in the ratio of the two lines A C and A B, which measure its height and its length.

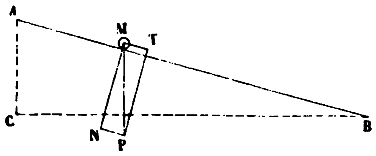

FIG. 7.—Movement of heavy bodies on an inclined plane.

In the case represented in the figure the force of gravity is reduced to little more than a quarter of its natural value.

The movement being considerably retarded by this arrangement, Galileo could easily measure the spaces traversed during each successive second.

But as the experiments of the inclined plane do not give results of great precision, the laws of falling bodies are determined at the present day by various instruments which are found in all physical laboratories, and which will be here described. Already in the seventeenth century, Riccioli and Grimaldi assured themselves of the exactness of Galileo's experiments, but they confined themselves to dropping a weight from the tops of towers of unequal heights, and measuring the times of the fall by the oscillations of the pendulum. In 1699 Father Sebastian invented a machine for the same purpose. Lastly, an English physicist, Attwood, constructed one which still bears his name: and in our time General Morin has invented another, which registers directly the results of the experiment.

The plan invented by Attwood to retard the movement of falling bodies is this: a very fine silken thread is passed round a wheel (Fig. 8), moving easily on friction rollers, the thread having at its two extremities metallic cylinders of exactly the same weight. In this state, the pulley, the line, and the weights remain at rest, because the two equal weights produce equilibrium. If an additional weight is placed on one of them, the system will be put into motion: the two portions of the line will be moved in an opposite direction, each still, however, keeping its vertical direction. But it will be at once seen that the speed of the fall will be the more retarded, as the additional weight is small compared with the sum of the two equal weights. Let us suppose that each of these weighs 12 grammes, and the additional one weighs 1 gramme only. The total weight of 25 grammes being put into motion by a force which is only a twenty-fifth part, it is

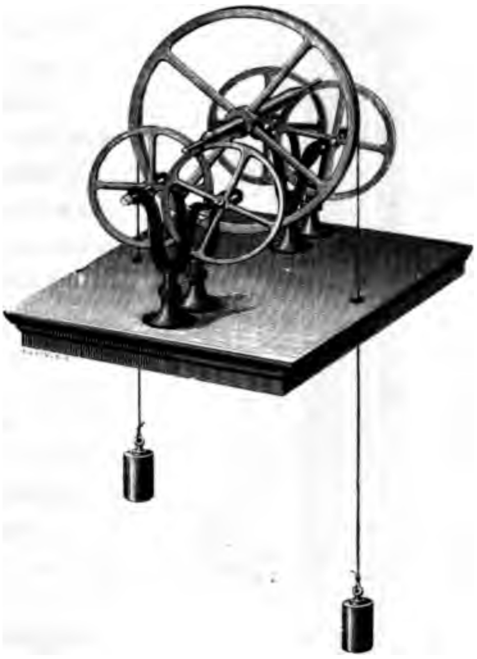

FIG. 8.—Pulley of Attwood's machine.

clear that the speed will be that which a falling body would possess if the intensity of gravity were twenty-five times less. Observation is thus rendered easy, without disturbing the laws of motion.

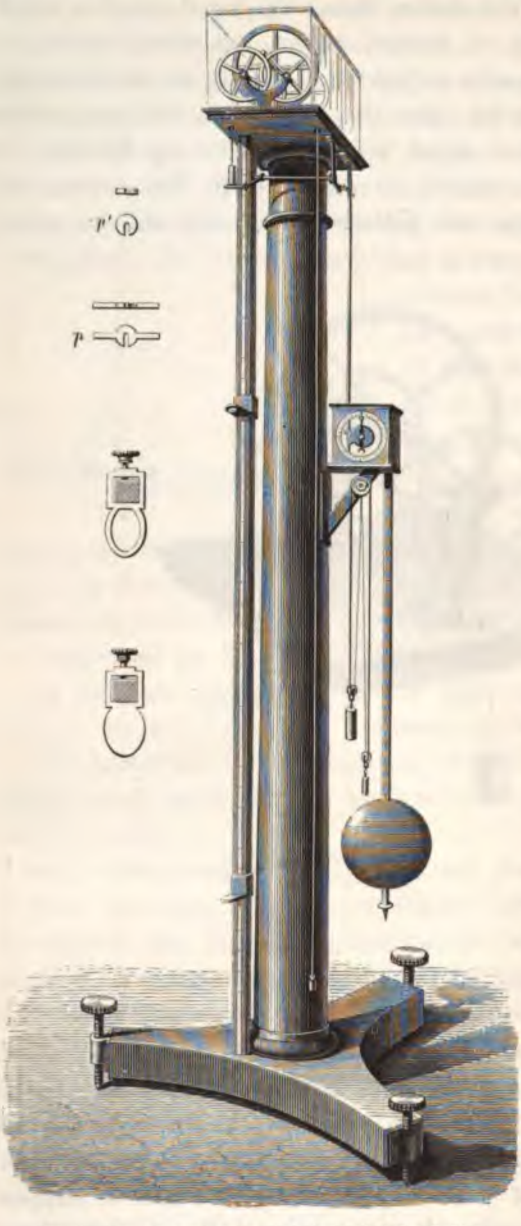

FIG. 9.—Experimental study of the laws of falling bodies. Attwood's machine.

Fig. 9 shows the arrangement of the machine. At the top of a column a pulley is seen, the axle of which rests on two systems of parallel wheels (friction rollers—see Fig. 8); then the line which passes round the pulley is stretched by equal weights on either side. A vertical scale, carefully divided, is placed behind one of the weights, on which scale the distance from the base of the weight to the zero of the scale, that is, the point of departure of the weight, may be read in each of its positions.

This scale has two moveable plates, which can be fixed by screws at any of its divisions. The lower plate simply arrests the movement of the system at will.

The other plate is in the form of a ring, and the opening is large enough to allow the weight suspended to the line p' to pass through, but on the other hand stops the additional weight p on account of its elongated form. A pendulum beating seconds is added: each movement of the second-hand makes a clear sharp noise, by means of which the passing seconds can be counted without looking at the dial. A contrivance attached to the clock enables each experiment to begin at the precise instant when the seconds' hand is at the zero of the dial, at the upper part of the latter. The additional weight, first placed above the weight which occupies the division 0 of the vertical scale, is suddenly let go by the action of the mechanism, and motion begins.

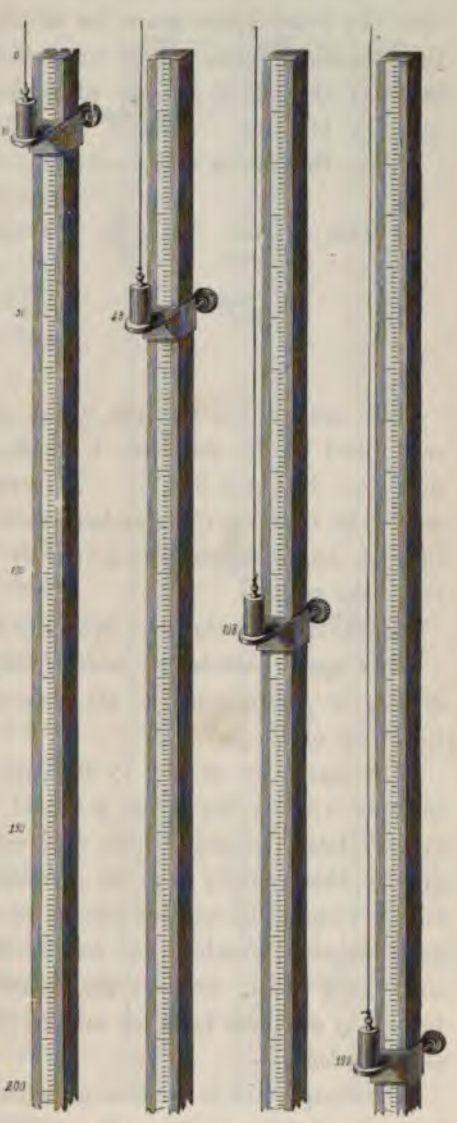

FIG. 10.—Experimental study of falling bodies. Law of spaces described.

The experiments are performed in this way: Place the lower plate in such a place on the column that the cylindrical weight surmounted with the weight p will touch it precisely at the commencement of the second second, which is determined by the coincidence of the second beat of the pendulum with the click of the weight on the plate. Suppose this point be at the twelfth division of the scale (Fig. 10). It is then observed, in conducting this operation successively during two, three, four seconds, &c., that the lower plate must be at the following divisions, in order that the click of the weight coincides each time with the successive beats of the clock. These divisions are marked by the numbers 48, 108, 192, &c.

Thus the spaces described are:—

After	1 second	 12	centimetres.	
„	2 seconds	 48	„	= 12 × 4
„	3 „	 108	„	= 12 × 9
„	4 „	 192	„	= 12 × 16
„	5 „	 300	„	= 12 × 25

The space, then, through which a falling body travels, must be multiplied by the numbers 4, 9, 16, 25 . . . . to obtain the space described during 2, 3, 4, 5 . . . . seconds of fall. If the additional weight be changed, the numbers which measure the spaces traversed in each second would change: their ratio, however, would still remain the same.

Here, then, is the first law, the one discovered by Galileo:

The space described by bodies falling freely under the action of gravity is proportional to the square of the time elapsed from the beginning of the fall.

It remains for us now to determine the law of velocity—that is, to learn what is the speed acquired after 1, 2, 3 . . . . seconds of fall. Whilst the body which falls remains subject to the action of gravity, this velocity goes on increasing at each instant during the fall, and cannot in consequence be directly observed. To render this determination possible, the continuous action of gravity must be suppressed at the moment the following second begins, so that the body may continue to move uniformly, *and in virtue of the acquired velocity alone.*

It is important to understand what is meant by the velocity of a body which falls, or, to speak generally, which is endowed with an accelerated motion. This velocity of motion at a given moment is measured by the space through which the body would travel uniformly in each of the following seconds if the force ceased to act, and the motion ceased to be accelerated. The ring of Attwood's machine realizes this hypothesis. It is sufficient to fix it successively at the divisions that were shown in the first experiment, then to find by trial at which part of the scale the lower plate must be in order that the weight, relieved of its overweight, may strike it at the beginning of the following second.

The experiment, supposing that p has the same mass as p', will give the following numbers: 36, 96, 180, &c. (see Fig. 11). Hence it follows that the uniform velocity of falling bodies, acquired after 1, 2, 3 . . . . seconds of fall, is :

After 1 second .	24	centimetres	per second.
„ 2 seconds.	48	„	„
„ 3 „ .	72	„	„

The velocity goes on increasing in proportion to the time; the second law which governs the fall of heavy bodies may then be thus enunciated :—

When a heavy body falls freely under the action of gravity, its speed is accelerated; its velocity, at any moment of the fall, is proportional to the time elapsed since the commencement of motion.

It follows also from the same experiments that the velocity acquired after one second of fall carries the body through double the space passed through during the first second; and it is easily seen that this is independent of the unit of time chosen.

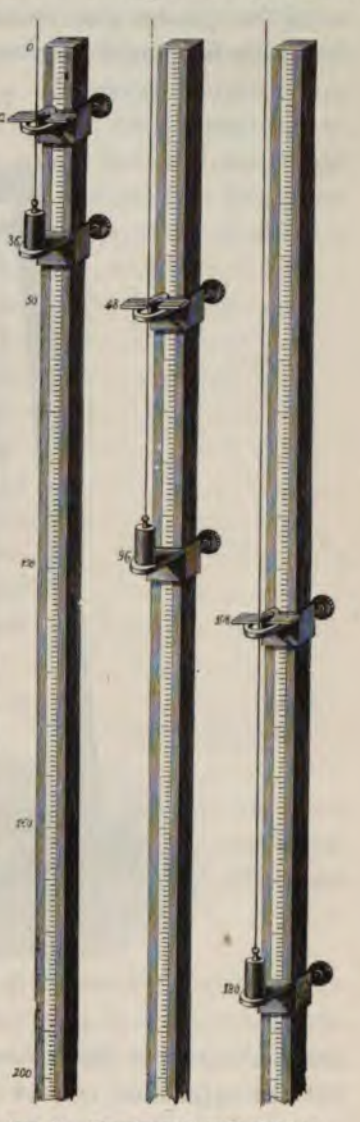

FIG. 11.—Experimental study of falling bodies. Law of velocity.

The same laws are proved experimentally by means of the machine invented by M. Morin, of which Fig. 12 gives a general view. A weight of a cylindro-conical form descends freely along two vertical rods: it is furnished with a pencil, which marks a continuous line on a cylinder covered with a sheet of paper.

If the cylinder were immoveable, the line marked by the weight during its fall would be a straight vertical line, which would indicate nothing as to the spaces traversed during successive seconds. But the cylindrical column is made to turn uniformly on its axis by the aid of a system of toothed wheels moved by the descent of a weight, and uniformity of rotation is produced by a fan-regulator, the spindle of which is connected with the train. Owing to this motion of the cylinder under the pencil in its descent, the pencil traces a curve, and an examination of this curve shows us the law

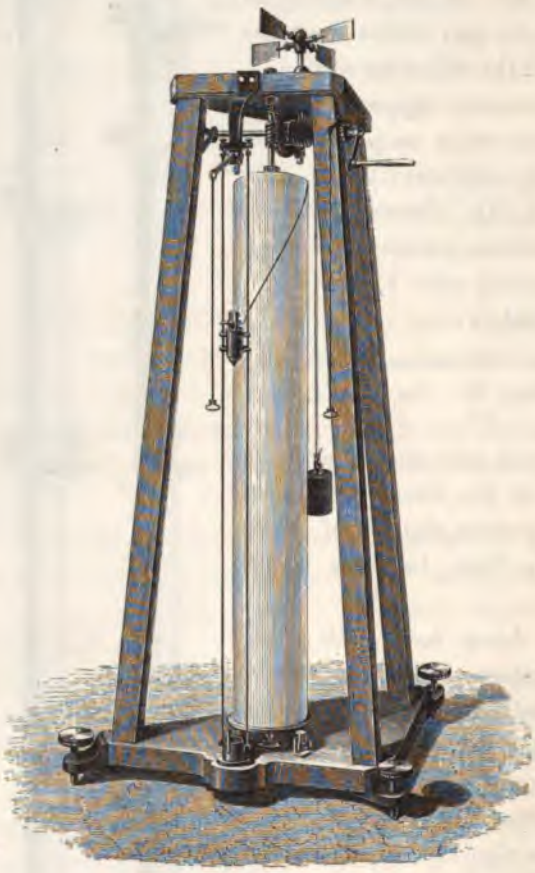

FIG. 12.—M. Morin's machine.

which governs the spaces described by the body during each second at different parts of its fall.

The curve is what is called in geometry a parabola, the fundamental property of which is as follows:—The distances of the successive points of the curve from a line drawn perpendicular to the axis of the parabola from its vertex, are proportional to the squares of the distances of these points from the axis itself. The line perpendicular to the axis being divided into five equal parts, the five distances from the vertex to the points of division, 0, 1, 2, 3, 4, 5, will be in the ratio of 1, 2, 3, 4, 5, but the five vertical lines let fall from the divisions will be in the ratio of 1, 4, 9, 16, and 25, that is, proportional to the squares of the first numbers.

Now the cylinder having turned uniformly on its axis, the equal portions of the circumference which separate the points of division of the horizontal line mark the successive seconds of fall of the weight, and the vertical lines are the spaces traversed.

As to the law of velocities, it is a direct consequence of that of spaces.

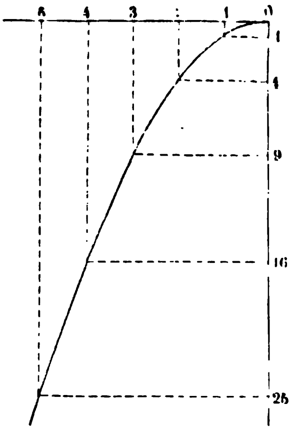

FIG. 13.—Parabola described by the weight in its fall.

It must not be imagined that the machines described give results of mathematical exactness. There are many hindrances, such as the friction of the parts, and the resistance of the air, which are opposed to such results; but the differences which arise from them are very slight.

The experiments made by means of Attwood's machine show moreover that gravity acts on the falling body in a continuous and constant manner. For the spaces traversed during successive seconds may be represented by the odd numbers 1, 3, 5, 7, 9, &c.; and as the velocities acquired at the commencement of the second and following seconds are 2, 4, 6, 8, 10, &c., it is seen that there is a constant difference, precisely equal to the space traversed during the first second. This difference marks the continuous action of gravity which, added to the acquired velocity, produces the effects observed.

Again, it is seen that if a body is thrown up vertically, the height to which it rises depends on the amount of force exerted,—moreover, its velocity decreases,—and when it descends under the action of gravity, its increasing speed at each point along its path is precisely equal to that which it possessed at the same point during its ascent.

The experiments made by the aid of Galileo's inclined plane and Attwood's machine are founded on an artificial diminution of the intensity of gravity, which, without changing the laws which govern their fall, retards the motion of falling bodies. But precisely on this account they do not enable us to measure the actual space traversed during one second of fall; and, moreover, the experiments must be made *in vacuo*. M. Morin's machine would give this space approximately, but the result would require corrections for friction and the resistance of the air. We shall see further on that the exact space has been determined by a more precise method.

The intensity of the force of gravity, moreover, we shall soon see, is not rigorously constant: it varies with the place, according to latitude, and even with the local features of the terrestrial crust. Lastly, in the same place, the intensity varies with the height above the ground, or with the depth beneath it.

It must be borne in mind that the following figures refer to the fall of bodies *in vacuo*, in the latitude of London, and at a little distance from the sea-level.

Under these conditions, a body travels during the first second of its fall, $16\frac{1}{12}$ feet. The velocity acquired after one second is then $32\frac{1}{6}$ feet, and it is this latter number which enables the force of gravity to be ascertained.

Fall in 1 second $= 1 \times 16\frac{1}{12} = 16\frac{1}{12}$
" 2 seconds $= 4 \times 16\frac{1}{12} = 64\frac{4}{12}$
" 3 " $= 9 \times 16\frac{1}{12} = 144\frac{9}{12}$
" 4 " $= 16 \times 16\frac{1}{12} = 257\frac{4}{12}$
" 5 " $= 25 \times 16\frac{1}{12} = 402\frac{1}{12}$

The time that a body takes to fall from a certain height, and the velocity acquired at the moment it touches the ground, may also be found in like manner.

In the case of a falling body the velocity is uniformly increased by gravity; in the case of an ascending one it is uniformly decreased.

To throw a body to a vertical height of 400 feet we must give it a velocity of 161 feet per second. This body, then, takes 5 seconds to ascend, and it would descend in the same time.

Let us repeat, in order that the reader may not imagine that the above numbers are found to be rigorously true in practice, that the resistance of the air is an element which much influences the movements of rising or falling bodies, and that the ratio of their weight to the surface which they offer to this resistance makes the result vary. The experiment made by a physicist of the eighteenth century, Désaguliers, before Newton, Halley, Derham, and many others, may here be referred to. Having dropped from the lantern above the dome of St. Paul's different bodies, such as leaden balls 2 inches in diameter, and bladders filled with air, of 5 inches in diameter, he found that the lead took 4½ seconds to fall through 272 feet, the height of the lantern above the ground; and that the bladders took 18½ seconds. Now, *in vacuo*, the space would have been passed through by both bodies in 4¼ seconds.

As the resistance of the air increases with the velocity of the fall, it is clear that bodies which fall from a great height, after having acquired a certain speed, finish their descent with a uniform movement. It has been calculated that a drop of water, the volume of which would be about the $\frac{1}{1000000000}$th of a cubic inch, would fall through perfectly calm air with a constant velocity of 5 inches a second, so that it would not travel more than 25 feet in a minute. This explains the relatively small velocity of raindrops, in spite of the considerable height of the clouds from which they fall.

CHAPTER IV.

LAWS OF GRAVITY.—THE PENDULUM.

The Pendulum—Galileo's observations—Definition of the simple pendulum—Isochronism of oscillations of small amplitude—Relation between the time of the oscillations and the length of the pendulum—Variations of the force of gravity in different latitudes—Borda's pendulum—Lengths of the pendulums which beat seconds in London, at the equator, and at the poles—Calculation of the oblateness of the earth—Experiments proving that the density of the earth increases from the surface to the centre.

NEWTON, seated one day in his garden at Woolsthorpe, saw an apple break off from the branch of a tree, and fall at his feet. It was this simple circumstance which suggested to him his profound researches on the nature of the force of gravity, and which made him ask whether this mysterious action, to which all terrestrial bodies are subjected, whatever their height in the atmosphere, whether at the bottom of valleys or at the top of the highest mountains, did not extend even to the moon. Thanks to the meditations of this great genius, we had not long to wait for the solution of this grand problem: but it was not till twenty years later that the edifice of which Kepler, Galileo, and Huyghens had prepared the foundation, which the successors of Newton finished, and which bears this triumphant superscription—"Universal Gravitation,"—was at last constructed in its majestic beauty.

Is this anecdote, repeated by all biographers of the great man, really true? It matters little: the essential point is that it is probable. But we should be mistaken if we imagined that it was of a nature to diminish the glory of the philosopher. Such things had happened millions of times before, to his ancestors and to his contemporaries. Such a fact as the fall of an apple could only excite such thoughts in a mind capable of the highest speculations, and moved by a will powerful enough to be always thinking them out.

It was a similar occurrence which caused Galileo to undertake his researches on the motion of the pendulum. He was then professor at Pisa, and, as we have before stated, was studying the laws of falling bodies. "One day," we read, "while present at a religious ceremony in the cathedral—paying, however, it would seem, very little attention to it—he was struck by a bronze lamp—a *chef-d'œuvre* of Benvenuto Cellini—which, suspended by a long cord, was slowly swinging before the altar. Perhaps, with his eyes fixed on this improvised metronome, he joined in the singing. The lamp by degrees slackened its vibration, and, being attentive to its last movements, he noticed that it always beat in the same time."[1]

It was this last observation which struck Galileo. The lamp, when the motion had nearly ended, described smaller and smaller arcs through the air, the period of swing, however, remaining the same. The able Italian philosopher repeated the experiment, and discovered the connection which exists between the period of oscillation and the length of the cord supporting the oscillating weight. Huyghens completed this beautiful discovery, and gave the mathematical law of the motion of the pendulum. Let us try to give an idea of this law, and show how it is connected with the theory of gravity.

Imagine a material and heavy point M′ (Fig. 14) suspended to one of the extremities of an inextensible line without weight. These are conditions which cannot be realized in practice, but they are accessible in theory. The line being fixed by its upper end, the action of gravity on the material point M′ stretches the line in the vertical direction, and the system will remain at rest.

Let us now suppose that the string is moved out of the vertical, still being kept tight and straight, and is then abandoned to itself in a vacuum. What will happen?

The action of gravity in the new position in M continues to act on the material point: but as this force always acts in a vertical direction, and as the string is no longer in that line, the resistance of the latter cannot completely annul the force of gravity.

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[1] J. Bertrand, "Galileo and his Works."

The material point, being attracted, will then fall: but as the string is inextensible, the fall can only be effected along an arc of the circle having its centre at the point of suspension A, and its radius the length of the string A M. It is as if the point were on an inclined plane, with its summit at M, and with an inclination gradually becoming smaller and smaller. Calculation shows that the movement will be effected with increasing velocity, until the time when the string will have returned to its vertical position; then, by virtue of its acquired speed, it will describe an arc equal to the first, but with decreasing velocity. Arrived at M″, at the same height as the point M, its motion will cease. It will be easily understood that the material point will recommence a movement similar, and perfectly equal to, the first, as the circumstances are the same, but in the contrary direction. This would be perpetual motion, if the supposed conditions could be fulfilled.

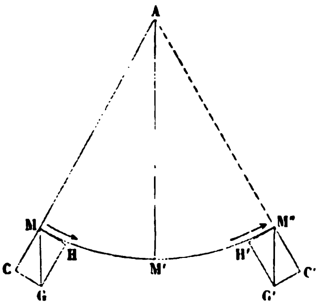

FIG. 14.—Oscillatory movement of a simple pendulum.

The ideal instrument we have just described is called the pendulum—the simple pendulum, in contradistinction to the real but compound pendulums, which may be actually constructed and observed.

The whole movement from M to M″ is called a swing or an oscillation, and its duration or period is obviously the time that the object takes to make the entire oscillation. It is scarcely necessary to state that the perpetuity of the oscillations or of the movement of the pendulum is purely theoretical. In reality, many causes exist which by degrees destroy the motion, and end by stopping it. The suspended body is not only a material point, but generally a metallic lens-shaped disc or ball. The rod is itself often large, and the resistance of the air destroys part of the motion of the pendulum at each oscillation. Let us add to these causes of retardation the friction of the knife-edge on the plane of suspension. Nevertheless, the laws of the simple pendulum have been successfully applied to the oscillations of compound pendulums, and the resistances which necessarily proceed from the relative imperfection of the pendulums have been taken into account with every possible precision. These laws, which it is so important to understand, and which have made the pendulum the best instrument for the measurement of time; the most precise indicator of the irregularities which the terrestrial spheroid presents; and a scale by the aid of which the density of our planet and of all the bodies of our solar system can be weighed, may now be stated.

The first law is that discovered by Galileo from observation: it is as follows:—"*The time of very small oscillations of one and the same pendulum is independent of their amplitude; the oscillations are isochronous—that is to say, they are all performed in the same time.*"

By small oscillations must be understood those the angle of which is less than four degrees. Within this limit the oscillations of greater amplitude are made in a very little longer time than the others, but the difference is very slight, and it is not until after a great number of oscillations that all the little differences of which we speak become perceptible.

It is theory, then, which demonstrates the isochronism of pendulum oscillations. But the law is easily verified by experiment. If we carefully count a considerable number of oscillations, and by a good chronometer measure the number of seconds elapsed, these two numbers obtained give, by simple division, the time of one oscillation, which will be found to be the same either at the beginning or at the end of the experiment.

This equality in the time required for passing through unequal distances under the influence of a constant force appears singular at first sight; but on reflecting a little it will be understood, without further demonstration, that in the case of greater amplitude the pendulum commences its swing in a direction more out of the vertical; the force of gravity, therefore, gives it greater velocity, by the help of which it soon makes up for the lead which a similar pendulum would have in describing an arc of less amplitude.

The second law which governs the motion of the pendulum establishes a relation between the time of the oscillations and the length of the pendulum.

Let us imagine a series of pendulums, the smallest of which beats seconds, the others performing their oscillations in 2, 3, 4 . . . seconds respectively. The length of these last would be 4, 9, 16 . . . times greater than the length of the first: the times following the series of the simple numbers, the lengths following the series of the squares of these numbers. This is expressed in a more general manner by saying: *The periods of oscillation of pendulums are in the direct ratio of the square roots of their lengths.*

Theory and observation agree in demonstrating this important law: but since we speak of experimental verifications, and since we know that it is impossible to realize a simple pendulum, it is time to state how the laws of this ideal pendulum are applied to the real or compound pendulums.

Pendulums of this kind are ordinarily formed of a "bob," or spherical ball of metal, with a rod adjusted in the direction of the centre of figure of the sphere or of the bob. This rod is fixed at its upper part into a sharp metal knife-edge, which rests on a hard and polished plane (Fig. 15). Such are the pendulums the oscillations of which control the motion of clocks.

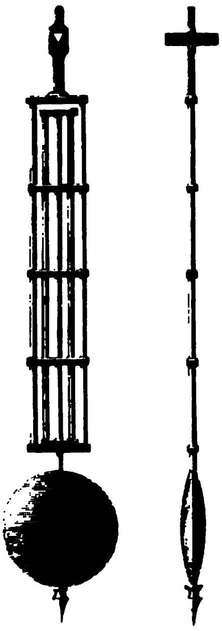

FIG. 15.—Compound pendulum.

In such a system, what is understood by the length of the pendulum is not the distance from the point of suspension to the lower extremity of the heavy body, but the approximate distance between this point and the centre of figure of the ball, when the rod of the pendulum is thin and the ball is made of very dense metal—platinum, for example. This last point then takes the name of centre of oscillation. We will show the reason for this fundamental distinction.

In a simple pendulum there is only considered to be one material point; in the compound pendulum their number, whether in the rod or in the ball, is infinite. It is as if there were a series of simple pendulums of different lengths compelled to execute their movements together. Their most distant particles find their movement accelerated; contrariwise, it is retarded in the case of those nearest the point of suspension. Between these extremes there is one particle, the duration of whose oscillations is precisely equal to those of a simple pendulum of equal length. Calculation makes us acquainted with the positions of this particle—that is to say, the point which we have just termed the centre of oscillation.

Let us now try to understand how it is possible, by means of pendulum observations, to solve several important questions which deal with the form of our planet and its physical constitution.

The periods of the small oscillations of a pendulum depend upon its length, according to the law we have just stated. But these two elements also depend on the intensity of the force of gravity in the locality where the oscillations are performed. Hence it follows that, if we observe with great precision the number of oscillations that a pendulum—the length of which is known with rigorous exactness—executes in a sidereal day, we shall be able to calculate the precise duration of a single oscillation, and thence deduce the intensity of the force of gravity—that is to say, twice the space which a heavy body falling *in vacuo* passes through in a second. This intensity is, in fact, connected with the length of the pendulum and the period of its oscillation.

It is by this method that the value was found which has been already given for the latitude of Paris—9·8094 metres.

This determination once obtained, it is possible to obtain by calculation the length of the pendulum which beats seconds. This length is at Paris 0·994 metre, at London 3·2616 feet. Now let us imagine that an observer travels from the equator to either pole. As the earth is not spherical, the distance of the observer from the centre of the earth will vary. Greatest at the equator, it will progressively diminish, will pass through a mean value, and will be the smallest possible at the poles themselves. Now, for this reason alone, the energy of the action of gravity in these different places must decrease from the poles to the equator. Another influence will also contribute to diminish the intensity of this force—that is, the rotation of the earth, the velocity of which, being *nil* at the two poles, progressively increases with the latitude, developing at each point a greater centrifugal force, which partly counterbalances the action of terrestrial gravity.[1]

For these two reasons, the intensity of the force of gravity will vary in different latitudes. How will our observer perceive it? By observing the oscillations of the pendulum, which furnishes us with two different but equally conclusive methods. The first method consists in employing a pendulum of invariable length; the rod and the bob, soldered together, are fixed to the knife-edge in a permanent manner. Such a pendulum, having a constant length, or at least only varying with changes of temperature, will oscillate more rapidly as the force of gravity is increased; so that, in going from the poles to the equator, the number of oscillations in a mean day will be smaller and smaller. Thus, a pendulum a metre in length, which at Paris makes *in vacuo* 86,137 oscillations in twenty-four hours, if carried to the poles would make 86,242, and at the equator would only make in the same time 86,017 vibrations.

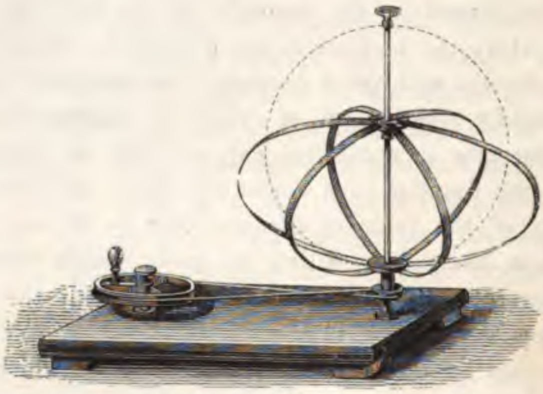

FIG. 16.—Effect of centrifugal force.

The other method is to set a pendulum in motion, to measure with the greatest care the number of its vibrations, and also its length at the time of the experiment; then to deduce the length of a simple pendulum beating seconds at the same station. The lengths of the pendulums beating seconds in different places, compared with each other, enable us to calculate the ratios which exist between the intensity of the force of gravity at those places.

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[1] The centrifugal force is rendered manifest in physical lectures by the aid of an apparatus shown in Fig. 16. Circles of steel rapidly turning on an axis take the form of ellipses flattened at the extremity of the axis, the flattening being more considerable as the velocity of rotation is greater.

We possess a great number of observations, made by one or other of the two methods in various regions of the two hemispheres, from the seventeenth century to the present time. The most illustrious men have associated their names with these investigations, which are of such importance to the physics of the globe.

We give here (Figs. 17 and 18) a sketch of the pendulum employed by Borda, so well known for the accuracy of his researches. This is the pendulum which was used in the observations made at Paris, Bordeaux, and Dunkirk, by Messrs. Biot and Mathieu.

Borda's pendulum was formed of a ball of platinum, suspended by simple adherence, and by the aid of a metal cap lightly covered with grease, to a fine metallic wire, which was attached at its upper extremity to a knife-edge similar to that which supports the pendulum-rods of clocks. The knife-edge rested on two well-polished fixed planes of hard stone, the position of which was perfectly horizontal. These planes were themselves fixed to a large bar of iron attached to supports fixed in a solid wall, in such a manner as to obtain perfect immobility.

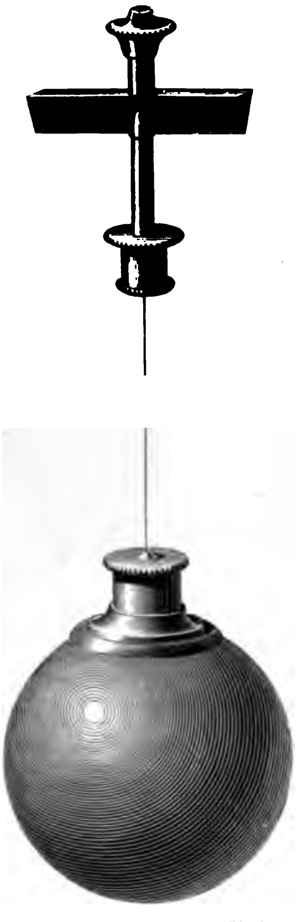

FIG. 17.—Borda's pendulum. Platinum sphere and knife-edge.

The oscillations were counted by comparing them with those of the pendulum of a clock placed against the wall, the movement of the clock being regulated by the stars. By the help of a telescope placed at a distance of ten metres, the successive coincidences of the two pendulums were observed, and from the number of the ncidences and the number of seconds elapsed the number of illations was deduced.

This number having been thus ascertained, the length of the ndulum was measured by operations of the greatest delicacy, the

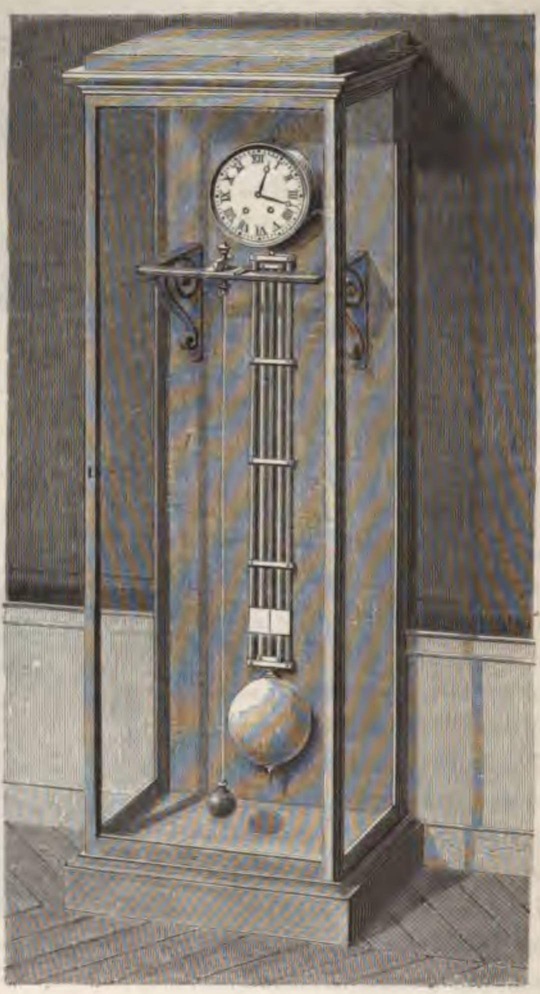

FIG. 18.—Borda's pendulum. Measurement of the time of an oscillation by the method of coincidences.

ils of which cannot be given here. They will, however, be nd in Vol. II. of Biot's "Physical Astronomy."

Having stated the length of the pendulums beating seconds at Paris and London, we will now give the length which calculation and observation have determined for similar pendulums located at the poles, equator, and at a mean latitude of forty-five degrees; the intensity of the force of gravity in these different places—that is to say, the number of metres indicating the velocity acquired in a second by heavy bodies falling *in vacuo*—is also shown.

	Length of the seconds pendulum. mm.	Intensity of the force of gravity. m.
At the equator	991·03	9·78103
At the latitude of 45 degrees .	993·52	9·80606
At the poles	996·19	9·83109

It must not be forgotten that the variation of the force of gravity in different parts of the earth depends, as we have before said, both on the form of the globe—which is not spherical, but ellipsoidal—and on the centrifugal force engendered by the velocity of rotation. The force diminishes therefore from the poles to the equator more than it would do without this rotation. But we know what proportion must be attributed to each of these causes in the phenomena observed. By the aid of pendulum observations it has been found possible to calculate the flattening of the earth, and to demonstrate in this manner the results of geodetic operations, as well as Clairaut's hypothesis on the increasing densities of the interior strata from the surface to the centre.

By careful comparisons of pendulum oscillations, executed in different regions of the globe, it has been found that they sometimes indicate a force of attraction much greater than that given by calculation; while in other regions the intensity is, on the contrary, more feeble than the elliptical form of the earth would require. As the excess of the action of gravity has been observed especially in islands situated in the open sea, whilst the opposite is found to be the case on the coast, or in the interior, of continents, it has been concluded that the water-level is somewhat depressed in the middle of the ocean, and that it rises in the vicinity of large extents of land.[1]

Here, then, we find the pendulum indicating inequalities in the curvature of the terrestrial spheroid.

[1] Saigey, "Physique du Globe."

By observing the difference of length of the pendulum which beats seconds at the top of a very high mountain and at the level of the sea in the same latitude, the density of the globe may be arrived at. Another similar method which has been employed consists in observing the oscillations of the pendulum at the sea-level and at a great depth in the interior, or at the sea-level and at the top of a high mountain. The present Astronomer Royal, Sir G. B. Airy, made some experiments in the Harton mines, on the vibrations of two pendulums placed, one at the surface, the other at the bottom of the mine, at a depth of 420 yards. The latter moved more quickly than the upper pendulum, and its advance of two seconds and a quarter in twenty-four hours showed that the intensity of the force of gravity was increased from the surface of the earth to the bottom of the mine by about $\frac{1}{20000}$th part of its value.

This result proves that the density of the terrestrial strata increases from the surface towards the centre; since, if it were otherwise, the attraction due to the interior nucleus would diminish with depth, and the oscillations of the pendulum would be more and more slow, which is contrary to the fact. The density of the strata comprised between the surface and the bottom of the mine being known, and the connection between this density and that of the nucleus being deduced from the acceleration observed, the mean density of the terrestrial globe may be calculated. The same research has been pursued by other methods, and has given slightly different results—a fact not at all astonishing in a problem of such delicacy.

To sum up: the terrestrial globe is acknowledged to weigh nearly five and a half times more than an equal volume of water. It is also proved, as we have already had occasion to state, that the density of the concentric strata of which the earth is formed continues to increase from the surface towards the centre. Physicists agree in giving—as a result of considerations which cannot find place here—for the density of the central strata, a value double the mean density, which itself is nearly double that of the superficial strata.

CHAPTER V.

WEIGHT OF BODIES—EQUILIBRIUM OF HEAVY BODIES—CENTRE OF GRAVITY—THE BALANCE.

Distinction between the weight of a body and its mass—Loss of weight which a body undergoes when it is taken from the poles to the equator—Centre of gravity in bodies of geometric form; in bodies of irregular form—The Balance; conditions of accuracy and sensibility—Balance of precision—Method of double weighing—Specific gravity and density of bodies.

> **"On precision in measures and weights depends the progress of chemistry, physics, and physiology. Measures and weights are the inflexible judges placed above all opinions which are only supported by imperfect observations."—J. MOLESCHOTT, *La Circulation de la Vie: Indestructibilité de la Matière.***

GRAVITY acts in the same manner on all bodies, whatever their form or size, or whatever the nature of their substance. This follows from the equal velocity which all bodies acquire in falling from the same height and in the same place. A heavy body, then, may be considered as the aggregation of a multitude of material particles, each of which is acted on individually by gravity (Fig. 19).

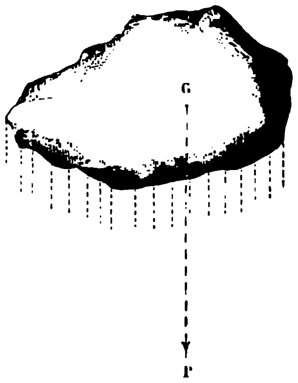

FIG. 19.—Weight of a body; centre of gravity.

All these equal forces are parallel, and thus produce the same effect as a single force equal to their sum. It is this resultant of all the actions of gravity which forms the *weight* of the body. The point where it is applied, and which is called its *centre of gravity*, is that which must be supported, in any position of the body, in order that the latter may remain in equilibrium. The centre of gravity is not always situated in the interior of the body: in some cases it falls outside it.

Although for simplicity's sake we used the word weight in the first chapter as a synonym for gravity, the force of gravity must not be confounded with weight: and it is also important to distinguish weight from mass. Mass, sometimes, is described as the quantity of matter which a body contains: but this definition is vague, and does not express the difference which exists between the two terms. An example will explain the precise sense which is given to this word in physical inquiries.

Let us take a heavy body—a piece of iron, for example. To determine its weight, let us suspend it to a spring, or dynamometer (see Fig. 1), such that its degree of tension will show the intensity of the action of gravity on the body. Let us notice the divided scale—the exact point where the upper branch of this instrument stops; and let us suppose that this first observation is made in the latitude of Paris, for instance.

Now transport the piece of iron and the dynamometer either to the equator or towards the poles. The intensity of the force of gravity is no longer the same: the spring will be less extended in one case, and more so in the other. The weight, as we ought to expect, after what we know of the variations of the force of gravity, has changed. And nevertheless we are dealing with the same quantity of matter: it is the same *mass* which, in the three cases, has been used for the experiment.

Thus, then, the quantity of matter—the mass—remaining the same, the weight varies, and in the same ratio as the intensity of the action of gravity varies; so that that which remains constant is the ratio, which should, for this reason, serve as a definition for the mass.

This variation in the weight of bodies when they are transported from one place to another in a different latitude would equally take place if the bodies were to change their altitude: that is, if their height above or below the sea-level were to be changed, their masses remaining always constant. But this change we shall not be able to prove by the aid of balances, because in these instruments equilibrium is produced by bodies of equal weight: and the variation in question will take place both in the weight to be measured and in the weight which is used as a measure.

Calculation shows that a mass weighing one kilogramme, or 1,000 grammes, at Paris, would not weigh more than 997·108 gr. at the equator. The same weight taken to either pole would exercise on a dynamometer the same tension as a weight of 1000·221 gr. at Paris.

Let us now return to the centre of gravity. It may be interesting, and moreover it is often useful, to know the position of the point which, when fixed or supported, keeps the body in equilibrium when it is subjected to the action of gravity only. When the matter of which the body is composed is perfectly homogeneous, and when its form is symmetrical or regular, the determination of the centre of gravity is purely a geometrical affair. Let us take the most ordinary cases.

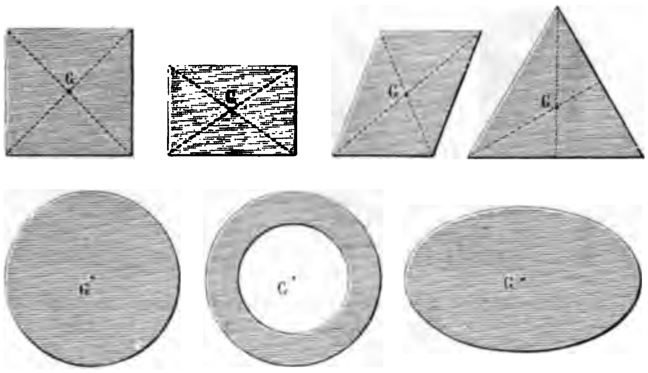

Fig. 20.—Centres of gravity of parallelograms, a triangle, a circle, a circular ring, and an ellipse.

A heavy straight bar has its centre of gravity at its point of bisection. In reality, the material bar is prismatic or cylindrical, but in the case where the thickness is very small in comparison with its length we may neglect it without inconvenience. The same remark is applicable to very thin surfaces, and they are considered as plane or curved figures without thickness. The square, rectangle, and parallelogram have their centre of gravity at the intersection of their diagonals (Fig. 20). The triangle has it at the point of intersection of the lines which fall from the summit of each angle on to the middle of the opposite side,—that is to say, at one-third the distance of the apex from the base, measured along these lines. If these surfaces were reduced to their exterior contours, the position of the centre of gravity would not be changed.

The centre of figure of a circle, a circular ring, or of an ellipse, is also its centre of gravity. Right or oblique cylinders, regular prisms, and parallelopipeds (Fig. 21) have their centres of gravity at the middle point of their axes. That of the sphere, and the ellipsoid of revolution, is at its centre of figure (Fig. 22). To find that of a pyramid, or a right or oblique cone, a line must be drawn from the vertex to the centre of gravity of the polygonal base, and the centre lies one-fourth the distance of the vertex from the base along this line.

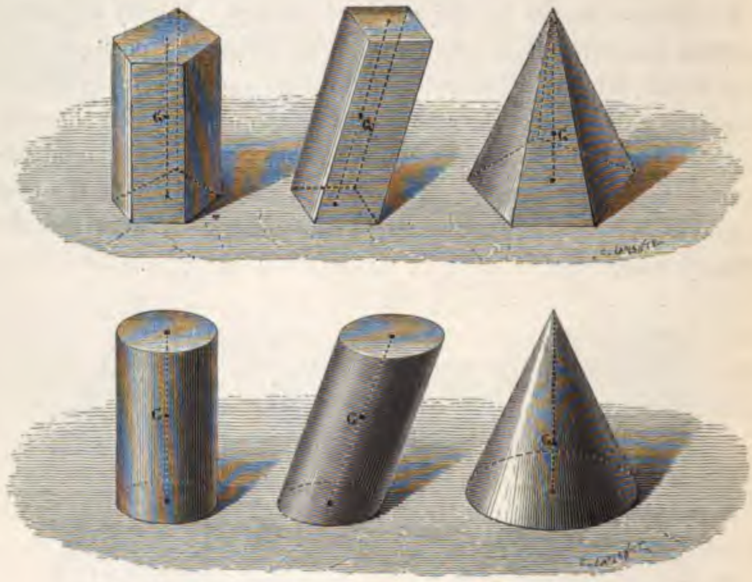

FIG. 21.—Centres of gravity of a prism, pyramid cylinder, and cone.

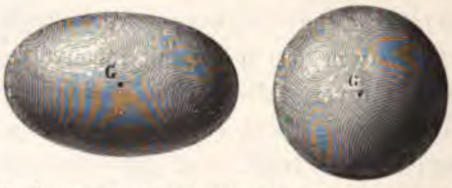

FIG. 22.—Centres of gravity of an ellipsoid and a sphere of revolution.

The above is for homogeneous bodies of geometrical form.

But, more often, the form is either irregular, or the material of the body is not equally dense in all its parts. In such cases, the determination of the centre of gravity is found by experiment. A simple means of finding it consists in suspending the body by a string. Once in equilibrium, the centre of gravity will lie along the prolongation of the string, the direction of which is then vertical. A second determination must then be made by suspending the body by another of its points; this furnishes a new line, in which the centre of gravity lies. The intersection of these two lines, then, gives the centre of gravity (Fig. 23), which may be sometimes inside, sometimes outside the heavy body.

The definition of the centre of gravity indicates that, when this point is supported or fixed, provided that all the material points of which the body is composed be united, equilibrium is secured. But this condition is difficult to fulfil, as very often the centre of gravity is an interior point, by which the body cannot be directly fixed or supported.

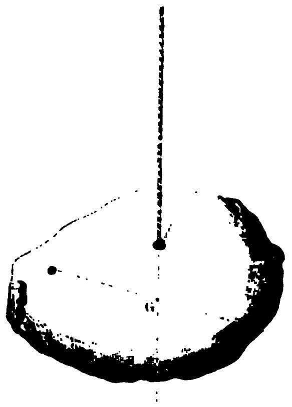

FIG. 23.—Experimental determination of the centre of gravity of a body of irregular form or non-homogeneous structure.

If the suspension is made by a string or flexible cord, equilibrium will establish itself; the centre of gravity will then be on the vertical line passing through the point of suspension. If, when this position is obtained, the body is disturbed, it will form a compound pendulum, and will execute a certain number of oscillations and will again come to rest. This is what is called *stable equilibrium*, and it is an essential condition of this kind of equilibrium that the position of the centre of gravity be lower than the point of suspension, so that when the body is disturbed the centre of gravity rises.

In general, in order that a heavy body be in equilibrium under the action of gravity, it is necessary and sufficient that its centre of gravity be in the vertical line passing through the point of support if this point is above it, or within the area of the plane of support if the fixed points are more or less numerous. Figs. 24 and 25 give examples of this. The Leaning Towers of Bologna and Pisa (Fig. 3 represents the second of these structures) are singular cases in which the equilibrium is preserved, owing to the circumstance that the centre of gravity of the edifice is in the vertical line falling within the base. But it is to be understood that the materials of which these towers are built are cemented together in such a manner, that each of them cannot separately obey the force which would cause its fall.

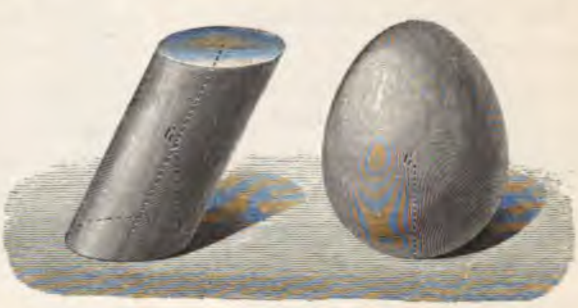

FIG. 24.—Equilibrium of a body supported on a plane by one or more points.

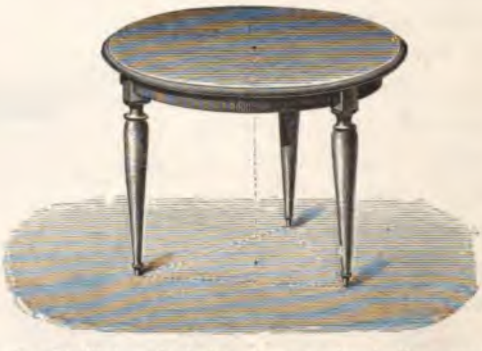

FIG. 25.—Equilibrium of a body resting on a plane by three supports.

The water-carrier and porter, represented in Fig. 26, take positions inclined either to the side or the front, so that the centre of gravity of their bodies and the load which they sustain, taken together, is in a vertical line falling within the base formed by their feet. The same condition is fulfilled by the cart (Fig. 27), which travels transversely along an inclined road: it remains in equilibrium while the centre of gravity remains vertically above the base comprised between the points where the wheels touch the ground. It would upset if this were not so, either from too great an inclination of the road, or from a too rapid movement impressed on the vehicle and its centre of gravity.

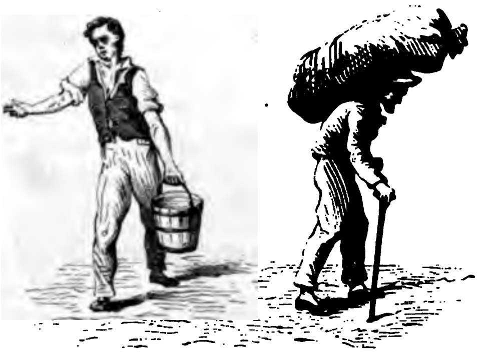

Fig. 26.—Positions of equilibrium of persons carrying loads.

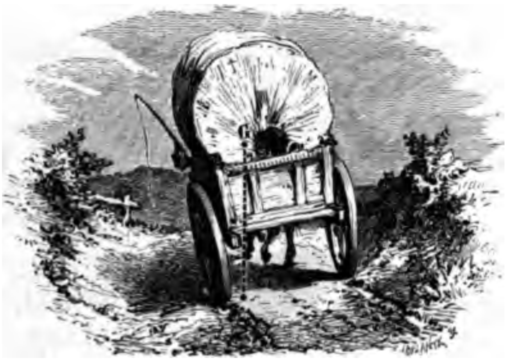

Fig. 27.—Equilibrium on an inclined plane.

When a body is supported by a horizontal axis, around which it can turn freely, its equilibrium may be either *stable*, *neutral* or *unstable*. It is stable, if the centre of gravity is below the axis neutral, if this centre is on the axis itself; and unstable, if the centre of gravity is above the axis. Fig. 28 furnishes an example of each of these cases.

To determine the centre of gravity of one or more heavy bodies is a problem which frequently finds numerous applications in various industrial arts. But another question, no less interesting and useful, is to determine that resultant of which the centre of gravity is the point of application, or, to use the common expression, to weigh bodies.

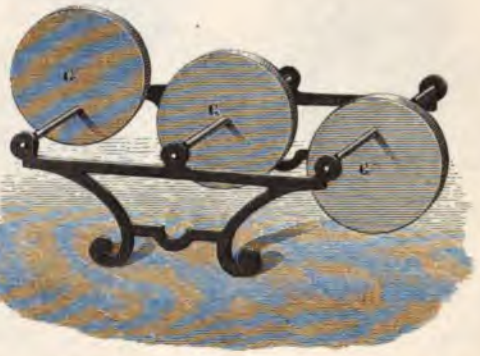

FIG. 28.—Stable, neutral, and unstable equilibrium.

The instruments destined to this use have received the name of Balances, or Scales. The Balances used are very varied in their forms and in their mode of construction, and we shall describe them in detail when we treat of the applications of physics. Here we shall confine ourselves to the description of the delicate balances used in scientific researches only.

The principle on which their construction is based is this:—A lever, a rigid, inflexible bar, resting at its centre on a fixed point, on which it can freely oscillate, is in equilibrium when two equal forces are applied to each of its two extremities.

To make a lever of this kind serve as a balance, it is indispensable that certain conditions, of which we are about to speak, be attended to in its construction.

It is necessary, first, that the two arms of the lever or beam A O, O B, be of equal length and of the same density, in order to produce equilibrium by themselves. The two scales, in one of which is placed the standard weight, in the other the body to be weighed, ought also to be of exactly the same weight.

In the second place, the centre of gravity of the system ought to be below the point or axis of suspension, and very near to this axis. It follows from this second condition, that the equilibrium will be stable, and that the oscillations of the beam will always tend to bring it back to a horizontal position, which is the indication of the equality of weight of the bodies placed in the two scales.

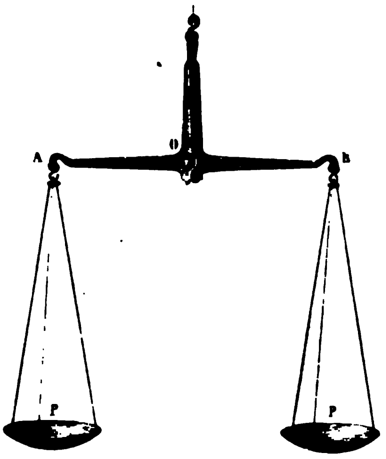

FIG. 29.—Scales.

These two conditions are necessary, in order that the balance be exact; but they are not sufficient to make it sensitive or delicate—that is, to cause it to indicate the slightest inequality in the weights by an unmistakeable inclination of the beam.

In order that a balance be very exact and delicate, it is further necessary: 1st. That the point, or axis of suspension, of the beam and of the two scales should be in the same right line. In this case, the sensibility is independent of the weights on the scales. 2d. That the beam be of a great length, and as light as possible; then the amplitude of the oscillations is greater for a given inequality of the weights; this is the reason which necessitates the centre of gravity of the balance being very near the axis of suspension of the beam, without, however, absolutely coinciding with it. Let us now show how these conditions are realized in the delicate balances used by physicists and chemists.

The beam is made of a lozenge shape, formed out of a metal plate of steel or bronze, and cut away in such a way as to diminish its weight without increasing its flexibility. Through its centre passes a steel knife-edge, the horizontal edge of which forms the fulcrum of the beam. This edge rests on a hard and polished plane—of agate, for example. The two extremities of the beam carry two other very small knife-edges, which, being horizontal and parallel to those of the principal one, support moveable steel plates, to which are attached the rods which hold the cups or scales.

The three edges which we have described must be placed exactly in the same plane, and their distances from each other must be perfectly equal. In the middle and above the beam, two buttons are fixed, one above the other, one of which is made like a nut, so that it can be screwed up or down at will. It is used to raise or lower the centre of gravity of the balance in such a way as to bring it nearer to or further away from the axis of suspension, and thus give to the balance the degree of sensibility required.

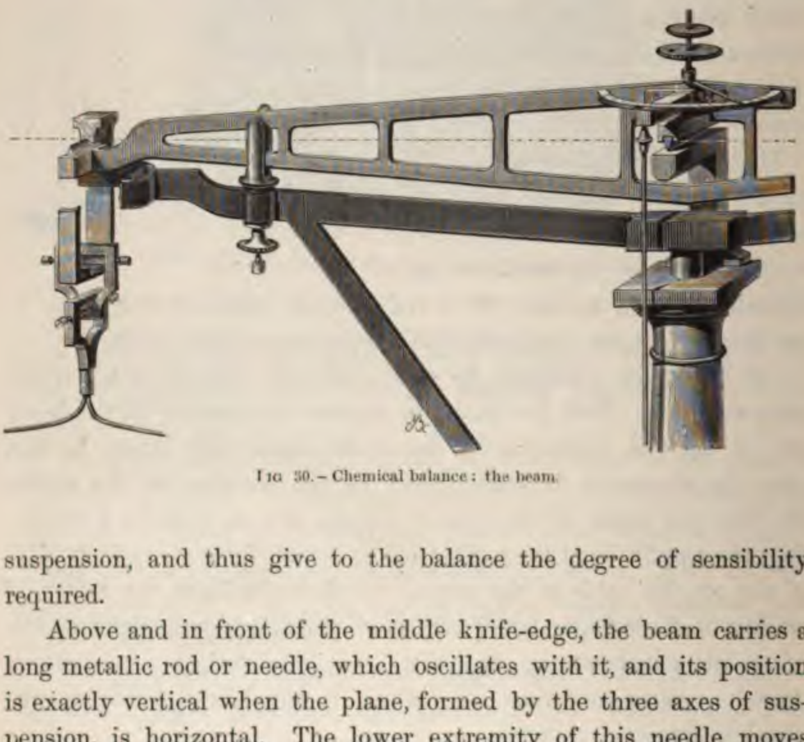

FIG. 30.—Chemical balance: the beam.

Above and in front of the middle knife-edge, the beam carries a long metallic rod or needle, which oscillates with it, and its position is exactly vertical when the plane, formed by the three axes of suspension, is horizontal. The lower extremity of this needle moves over an ivory arc, the zero division of which corresponds to this last position, and determines it. On either side of zero, equal divisions indicate the amplitudes of the oscillations of the needle: if these amplitudes be equal on each side, we are assured of the horizontality of the beam and of the equality of the weights in the scales.

A balance thus constructed should be placed on a firm plane; and by the use of the elevating screws placed at the foot of the instrument, and by observing the needle, its position must be made exactly horizontal before beginning work. To avoid the influence of currents of air and the deterioration proceeding from dampness or other atmospheric agents, the balance is also enclosed in a glass case, which is shut during the weighing, and is only opened to insert or remove the weights and the substances to be weighed. Chloride of calcium is also placed in the case to absorb the moisture. Moreover, when the apparatus is not in use, a metallic fork is made to raise the beam by means of rackwork enclosed in the column, so that the knife-edges may keep their sharp edges, which, without this precaution, the pressure would in time render dull.

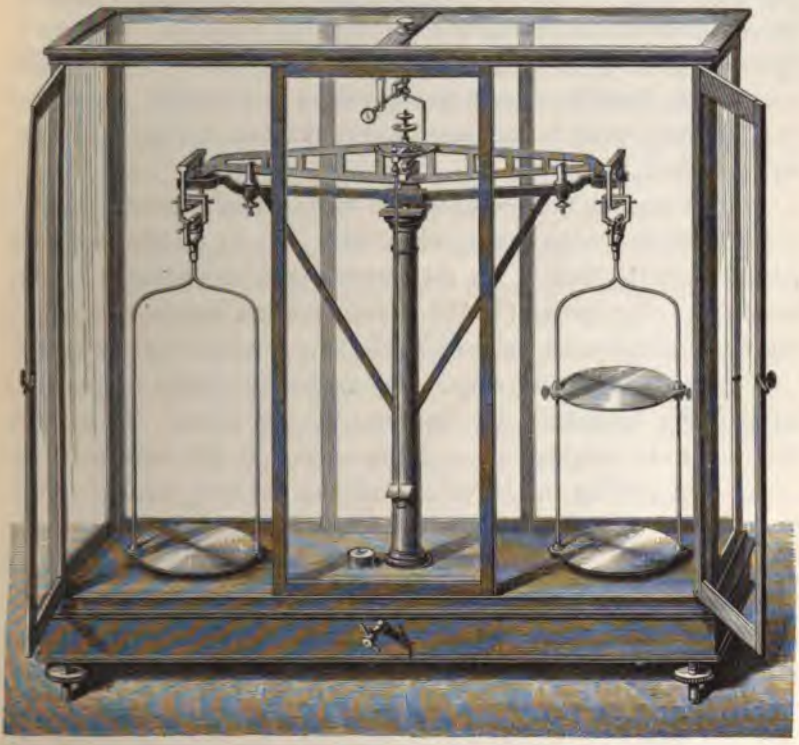

FIG. 31.—Chemical balance.

We now see with what precision the conditions of exactitude of a balance destined for scientific uses, such as the instrument just described, are realised. This precision is indispensable in the delicate determinations required in physical researches and modern chemistry. But they do not suffice: the operator must also add the ability which experience produces, and precautions on which we cannot enter.

It is unnecessary to state that the precision of the balance would be completely useless if the weights were not themselves rigorously exact. Sometimes, besides the series of mean weights, the operator possesses another series of small weights, which he has carefully constructed himself of very fine platinum wire, which he uses for weights lower than a gramme, as decigrammes, centigrammes, and milligrammes.

At the present time, balances are made delicate enough to detect a milligramme (0·0154 grain) when each scale is charged with five kilogrammes (13·39 lb.). In the balances used in chemical analysis, tenths of milligrammes (0·00154 grain) even are weighed: but then the total charge must be very small, two grammes for example.

Physicists frequently employ the method of double weighing, to remedy any inequality in the arms of the beam. They place the body to be weighed in one of the scales, and then establish equilibrium by putting in the other scale an ordinary tare formed of leaden shot. In this state, if the arms be not exactly the same length, the apparent equilibrium does not prove the equality of the weights. But if, on removing the body, it is replaced by weights graduated until equilibrium be again established, it is easily understood that these weights exactly represent the weight sought for, since they produce the same effect as the body itself does under the same conditions.

It will be seen further on, that the weight of a body is modified by the medium in which it is weighed, so that it is lessened by the weight of the fluid which it displaces. On the other hand, its volume varies with the temperature, and consequently the same body does not always displace the same quantity of fluid; hence the necessity of taking account of these elements of variation, unless the precaution is taken of weighing in a space void of air—that is to say, *in vacuo*.

The unit of weight generally adopted by scientific men of all countries is that of the metric system of weights and measures—the *kilogramme.*

A cubic decimetre of distilled water, weighed *in vacuo* at the temperature of four degrees centigrade above its freezing-point, in the latitude of forty-five degrees, and at the level of the sea, weighs one kilogramme. Such is the exact definition of the unit of weight. It must not be forgotten that, if the weight varies with the latitude and with the height above the level of the sea, the variation does not manifest itself in a balance, because it affects in the same manner the weights placed in both scales. These causes of error may, therefore, be neglected when the balance is employed.

We may state also, in bringing this chapter to a close, what is understood by *specific gravity* and *density:* further on, we shall see how the values in question are experimentally determined. Equal volumes of different substances have not the same weight; a block of stone weighs more than a piece of wood, and less than a piece of iron, of the same dimensions: this is a fact easily proved, and known by every one. Let us suppose that we take, as the unit of volume of each, the cubic decimetre for instance, and weigh them all at a constant temperature, the values obtained will be what are called the *absolute weights* of these substances.

The absolute weights would vary, if the unit of weight were changed, but their relations would remain invariable. It is then usual to take one of them for unity: the weight of water is thus chosen, because water is a substance spread all over the earth, and it is easily procured in a state of purity. The weight thus expressed is called *relative* or *specific weight,* or specific gravity.

In making similar comparisons between the masses of different substances with a unit of volume, we determine also what is called the *relative density* of substances. As the numbers thus obtained are precisely the same as the specific gravity, it often happens that they are confounded one with the other, under the common denomination of density, which is clearly an error.

CHAPTER VI.

WEIGHT OF LIQUIDS.—PHENOMENA AND LAWS OF EQUILIBRIUM: HYDROSTATICS.

Difference of constitution of solids and liquids; molecular cohesion—Flowing of pulverulent masses—Mobility of the molecules of liquid bodies—Experiments of the Florentine Academicians; experiments of modern philosophers—Pascal's law of equal pressures—Horizontality of the surface of a liquid *in equilibrio*—Pressure on the bottom of vessels; pressures normal to the sides; hydraulic screw—Hydrostatic paradox; Pascal's bursting-cask—Equilibrium of superposed liquids; communicating vessels.

PHENOMENA the most curious and the most worthy of attracting our attention are daily passing before our eyes without our taking any notice of them, much less considering the causes which give rise to them. Such are, for example, the different appearances under which we see bodies, sometimes solid, sometimes liquid, sometimes gaseous, and sometimes passing successively through the three states. In what does ice differ from water, and how does the latter transform itself into vapour? What difference is there between the arrangements of the molecules which constitute these three forms of one substance? These are questions of very difficult solution, on which science possesses few data, which we will review in the several chapters of this work. We will now confine ourselves to those which are necessary to the understanding of the phenomena we are about to describe.

That which distinguishes a solid body when it is not submitted to mechanical or physical forces capable of breaking it, or of making it pass into a new state, is its constant form. Let us consider a stone or a piece of metal. Its particles are so solid that they keep their mutual distances, only separating from each other under an exterior force, more or less strong. It follows that the position of the centre of gravity of the body remains invariable, and that whatever movement a stone receives, whether it is thrown into the air or falls under the action of gravity, all its particles will participate at the same time and in the same manner in the motion. Cohesion is the force which thus unites the different molecules of a body one to the other.

It happens, when a solid body is reduced to very fine particles—to small dust—that this cohesion appears to be, if not annulled, at least considerably diminished. Hence it is that it is difficult to maintain a heap of sand in the form of a high cone: the grains slip one over the other, and their movement along the slope of the mass is somewhat analogous to the flowing of a liquid on an incline. This analogy appears still more striking when we fill a vessel with fine powder, and make a hole in the bottom. The flow resembles that of a liquid (Fig. 32), but in appearance only, for each grain, however small it be, is a mass which has all the properties of a solid body, and, indeed, does not differ from one.

What then, from a physical point of view, is the special characteristic which distinguishes liquids from solids?

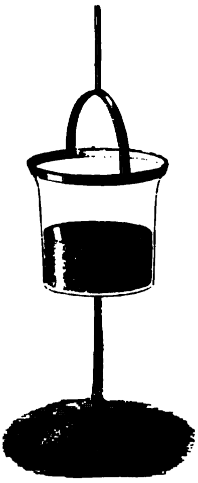

FIG. 32.—Flowing of sand.

It is that, whilst in the latter molecular cohesion is strong enough to prevent the movement of its different particles, in liquids, on the contrary, this force is nothing, or nearly nothing. Hence the extreme mobility of their particles, which slide and roll one over the other under the action of the slightest force. In consequence of this mobility, a liquid mass has in itself no definite form; it takes, when in equilibrium, the form of the vessel or natural basin which contains it, the walls of which prevent it from moving under the action of gravity.

It must not be imagined from this that there is no cohesion in liquids. When a liquid mass is in motion, its particles do indeed change place, but they are not isolated or separated, as happens in the case of sandy matters: the distance between the particles does not change, and, if the form is modified, the volume remains invariable. When a solid disc is applied to the surface of a liquid which moistens it (Fig. 33), it requires a certain effort to separate it from the liquid, and the liquid stratum which the disc takes with it shows that this effort was necessitated by the force which united the liquid molecules to each other. It would be the same if a rod were dipped in a liquid susceptible of moistening the substance of which the rod is formed. On drawing it out, a drop of liquid would be seen suspended at the end. Lastly, the spherical form which dew-drops, when deposited on leaves, or small drops of mercury lying on a solid surface (Figs. 34 and 35), present, is explained by the preponderance of the molecular cohesion over the action of gravity, which otherwise would tend to spread out the small liquid masses in question over the surfaces which sustain them. Nevertheless, this cohesion is very slight, as may be shown by the mobility of the particles and the facility with which the cohesion is overcome: a mass of water projected from a certain height falls to the ground in a shower of spray, due, as we have already seen, to the resistance of the air.

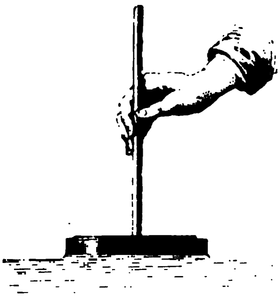
FIG. 33.—Cohesion of liquid molecules.

FIG. 34.—Spherical form of dew-drops.

Moreover, there is a great difference in this respect between various liquids. Some are viscous, and their molecules are but slowly displaced, requiring some time to take the form of the vessels which contain them: such are resins, and sulphur at certain temperatures. Soft bodies form, in this manner, a transition state between solids and liquids.[1] Other bodies, such as the ethers and alcohols, possess a great degree of liquidity, and even pass with the greatest facility into a state of vapour. Lastly, there is a certain number of liquids, like water, in a degree of liquidity which is a mean between these two extremes. We shall see further on that heat and pressure have a very important influence on these different states.

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[1] The cohesion of the particles which form solid bodies can be overcome by sufficient pressure. Some experiments of great interest made by M. Tresca have proved the fact—in appearance paradoxical—that the hardest solids can, without changing their state, flow under great pressure, like liquids.

Whatever these differences may be, the phenomena which we are about to pass under review are manifested by all liquid bodies, to degrees which vary only according to their more or less perfect liquidity.

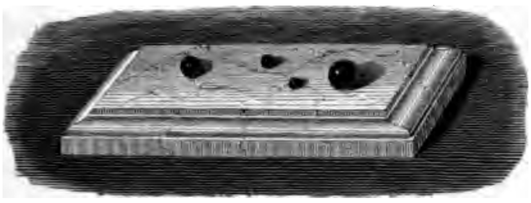
FIG. 35.—Cohesion of liquid molecules ; drops of mercury.

Most people have heard of the celebrated experiments made at the end of the eighteenth century by the physicist of the Academy del Cimento, of Florence, on the compressibility of liquids. Does water, or more generally speaking, does any liquid change its volume, when submitted to a considerable mechanical pressure ? Such was the question which these men asked themselves, and which they believed they solved negatively. They caused a hollow silver sphere to be made, filled it with water, and immediately hermetically sealed it. Having then strongly compressed it, they saw the water oozing through its walls. They made other experiments with the same result, and they concluded that liquids do not diminish in volume under the action of the greatest mechanical forces, or, in other words, that they are incompressible.

But more recent experiments have invalidated those of the Florentine Academicians. The compressibility of water and many other liquids has been demonstrated. Canton in 1761, Perkins in 1819, Oersted in 1823, and, more recently, Despretz, Calladon and Sturm, Wertheim and Regnault, have measured with continually increasing accuracy the diminution of volume brought about in sundry liquids subjected to a determinate pressure. We shall see further on that this diminution is extremely slight,—so slight that it need not be taken into account in the study of hydrostatic phenomena. We will now give a description of the more important of these phenomena.

Imagine two cylinders of unequal diameter communicating at their bases by a tube (Fig. 36). Two perfectly fitting pistons move freely in the interior of each of them, and the tube and the cylinders below the pistons are filled with water. We find by this experiment that, in order to obtain equilibrium in the instrument, if the charge of the piston of the small cylinder, added to its own weight, is, for example, one kilogramme, or one pound, the largest piston must be charged, its own weight included, by as many times one kilogramme or one pound as the surface of the large cylinder contains that of the small one.

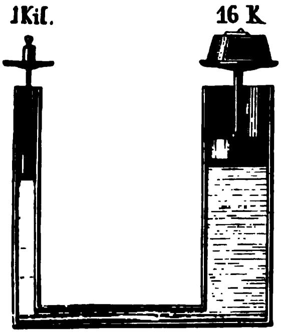

Fig. 36.—Principle of the hydraulic press.

In the example represented in Fig. 36 one kilogramme balances sixteen. It seems as if the pressure exercised by the surface of the small piston were transmitted, without any modification of its energy, through the liquid to each equal portion of the surface of the large one.

Such is, in fact, the principle on which rests the construction of a machine of the greatest utility, which will be described in the applications of physics, and which is known under the name of the hydraulic press or ram. The discovery of this principle is due to Pascal: it is a consequence of the mobility and elasticity of liquid particles. It may be formulated as follows:—*Pressure, exercised on a liquid contained in a closed vessel, is transmitted with the same energy in all directions.* By this it must be understood that, if we take on the liquid or on the interior walls of the vessel a surface equal to that on which the pressure is exercised, this surface will undergo a pressure exactly equal to the first; if the surface which receives the pressure is double, triple, quadruple, &c., of that which transmits it, it will support a double, triple, and quadruple pressure. So that, if we open in the sides of the vessel orifices of any dimensions, it is necessary, to maintain equilibrium, to exercise on the pistons which shut these orifices pressures proportional to their surfaces (Fig. 37). In order to prove this by experiment, it is necessary, in measuring the pressures exercised or transmitted, to take into account the pressures which proceed from the force of gravity, or that which the liquid exercises on itself or on the walls of the vessel by its own weight. The experiment shown in Fig. 36, and actually realized in the hydraulic press, is an evident consequence of Pascal's principle.

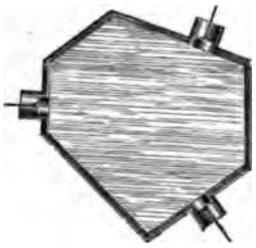

FIG. 37.—The pressure exercised on one point of a liquid is transmitted equally in every direction.

We have seen—and it is a fact which every one can prove by observation—that the direction of the plumb-line is perpendicular to the surface of a liquid at rest. It can be easily understood that it could not be otherwise. In fact, when the surface of a liquid is not plane and horizontal, a particle such as M (Fig. 38) finds itself on an inclined plane, and, in virtue of the mobility proper to liquids, it glides along the plane under the influence of its own weight. Equilibrium will be impossible until the cause of the agitation of the liquid having ceased, the surface becomes by degrees level, and is exactly plane or horizontal. The large liquid surfaces of the seas, lakes, and of pools even, are rarely in repose. The agitations of the air, high winds, or light breezes, are sufficient to produce those multitudes of moving prominences, which are called waves, or simple ripples. But if, instead of taking into consideration a small portion only, we embrace with the sight or in thought an extent of sufficient radius,—or if we contemplate this extent from a considerable distance,—the inequalities are effaced on the whole; the liquid appears to be at rest; and its surface is clearly a horizontal plane.

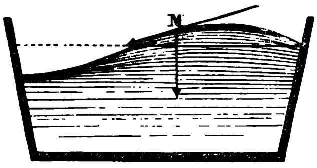

FIG. 38.—The surface of liquids in repose is horizontal.

We must always bear in mind that the earth is spheroidal; that the verticals of the different places are not parallel; that the real surfaces of the seas and great lakes participate in its curvature, as is proved by various optical phenomena described in one of our preceding works.[1] But this only goes to confirm the essential condition of the equilibrium of a liquid contained in a vessel and submitted to the action of the force of gravity only.

The exterior surface of a liquid in equilibrium is always level, or plane and horizontal. This is on the exterior. Let us now see what happens in the interior. Each liquid particle possessing weight, it may be considered as a pressure exercised vertically, and ought to transmit itself in every direction to the other portions of the liquid, and to the walls of the vessel which contains it. What is the resultant of the pressure of all the particles? The following experiment will answer this question.

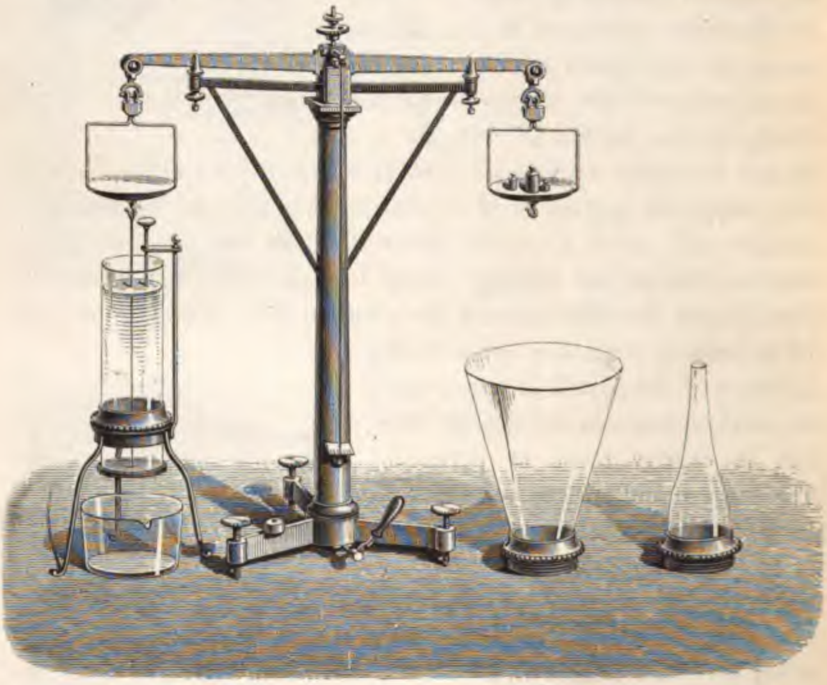

FIG. 39.—Pressure of a liquid on the bottom of the vessel which contains it.

Let us take a cylindrical vessel, without a bottom, supported by a tripod of a certain height (Fig. 39). A flat disc, in the form of a plate, suspended by a wire attached to one of the arms of a balance, is applied exactly to the lower edges of the cylinder, so as to form a bottom to it. In the other scale a counterpoise is placed equal to the difference between the weight of the cylinder and that of the disc. Lastly, standard weights are added, which cause the disc to press against the bottom edge of the cylinder. Water is then poured into the latter. The pressure of the liquid on the moveable bottom by degrees increases; when it has become equal to the added weights, the least excess of liquid detaches the disc, and the water flows out. But the pressure diminishes by this outflow, and the disc again adheres closely to the cylinder. A pointer which touches the surface of the water marks its level at the moment of equilibrium.

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[1] See "The Heavens."

It is seen from this first experiment, that, as we should expect, *the pressure exercised on the bottom of the vessel is precisely equal to the weight of the liquid.*

If now we repeat the experiment with a vessel with the same sized orifice at bottom as the cylinder, but wider at the top, and consequently of much greater volume, we find identically the same result—that is to say, the same weight counterpoises a column of liquid of the same height. The result is the same if a vessel narrowed at the top is employed, provided that the surface of the base remains the same.

Thus, the pressure exercised by the weight of a liquid on the bottom of the vessel which contains it is independent of the form of the vessel, but proportional to the height of the liquid, and lastly, equal to the weight of a liquid column of the same height, having the bottom of the vessel for a base.

The experimental demonstration of the first part of this law may also be shown by the aid of Haldat's apparatus; but the measure of the pressure is not directly given, as in the first method. It is shown by the elevation of a column of mercury in a tube, as shown in Fig. 40.

If, instead of inquiring the degree of pressure on the bottom of the vessel, we wished to find that exercised on the surface of a liquid stratum, or the sides of the vessel, this pressure would be found to be the same, with equal surfaces and the same depth; for it is also measured by the weight of a vertical liquid column, having the pressed surface for its base, and for its height the distance of the stratum from the surface of the liquid.

The following experiment demonstrates this law in the case of a surface taken on an interior horizontal stratum:—

A cylinder, open at the two ends, and furnished with a disc or moveable covering, which serves it as a bottom, is plunged vertically into a vessel full of water (Fig. 41). The hand is obliged to exert an effort in introducing the cylinder, which proves that the liquid exercises an upward pressure which holds the disc against the edges of the cylinder and prevents the water from getting in. If, now, water is poured into the tube, equilibrium continues as long as the interior level is lower than the exterior one. At the moment when equality is attained in the levels, and even a little before, on account of the weight of the disc, the latter gives way, and equilibrium is destroyed. The same result is always produced to whatever depth the cylinder is immersed. Hence this law:—

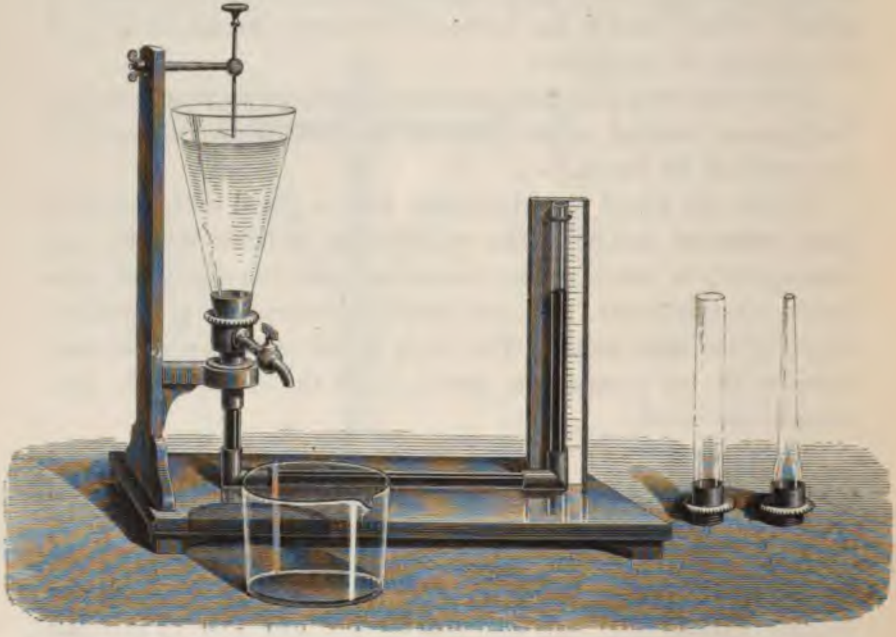

FIG. 40.—Pressure of a liquid on the bottom of a vessel: Haldat's instrument.

In a liquid in equilibrium under the sole action of the force of gravity, the pressure on a definite point of the same horizontal stratum is constant; it is measured by the weight of a liquid column having for base the area of the surface under pressure, and for height the vertical depth of the stratum.

The lateral pressures on the walls are measured in the same way. It must be added that their pressure is always exerted normally, that is to say, perpendicularly to the surface of the walls, so that it is exerted in a direction contrary to the action of gravity, if the wall is horizontal above the liquid.

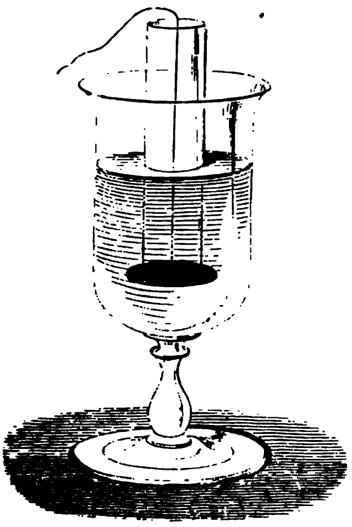

FIG. 41.—Pressure of a liquid on a horizontal stratum.

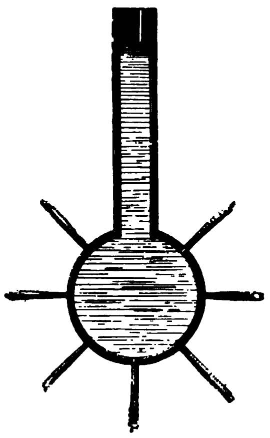

FIG. 42.—The pressures of liquids are normal to the walls of the containing vessel.

We will give some experiments which prove the existence and the directions of these pressures.

A cylinder (Fig. 42) is terminated by a very thin metallic ball pierced with holes in all directions. If it be filled with water, it will be seen to spout out through all the orifices, and the direction of the jet is always normal to the portion of surface whence it escapes. In the rose of a watering-can the water escapes in virtue of this property of liquids to press laterally against the walls of the vessels which contain them.

The hydraulic tourniquet shows the lateral pressure exerting itself in two opposite directions at the two extremities of a doubly curved horizontal tube (Fig. 43). If this tube were not open, the lateral pressure on the end would be counterbalanced by an equal and contrary pressure at the elbow, and the instrument would remain at rest; but the orifices at each extremity permit two liquid jets to escape, and as the pressure on each elbow is no longer counterbalanced, a backward movement follows and a rotation of the tube is set up.

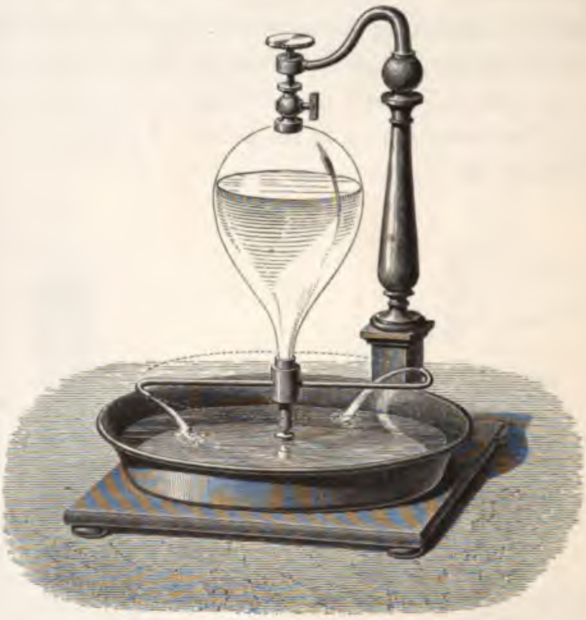

FIG. 43.—Hydraulic tourniquet.

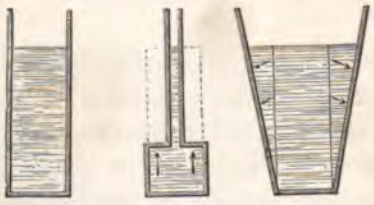

FIG. 44.—Hydrostatic paradox.

The pressures, lateral or otherwise, exerted normally on the walls explain all that is peculiar in the equality of pressure on the bottom of vessels of different forms. In a wide-mouthed conical vessel, the lateral walls support the excess of the total weight of the liquid over that of the column which measures the pressure on the bottom. In a narrow-topped vessel, the walls are subjected to pressures in a direction opposed to that of the force of gravity, and the amount of this pressure is precisely equal to that which is wanting to form the liquid cylinder, the weight of which is equivalent to the pressure on the horizontal bottom of the vessel (Fig. 44).

Thus is explained the phenomenon, which at first appears so singular, of liquid columns very different in weight when they are measured in the scale of a balance, nevertheless exerting the same pressure on a unit of surface in the bottom of a vessel, if the weight of the liquids be equal. Pascal proved this fact, which is called the hydrostatic paradox. He burst the staves of a solidly constructed barrel, filled with water, the bung-hole of which was surmounted by a very narrow, high tube, and he did this by simply filling this tube with water; that is to say, by adding to the whole weight an insignificant addition (Fig. 45). The walls of the barrel had to support the same pressure as if they had been surmounted by a mass of water having a base equal to the bottom of the barrel and the same height

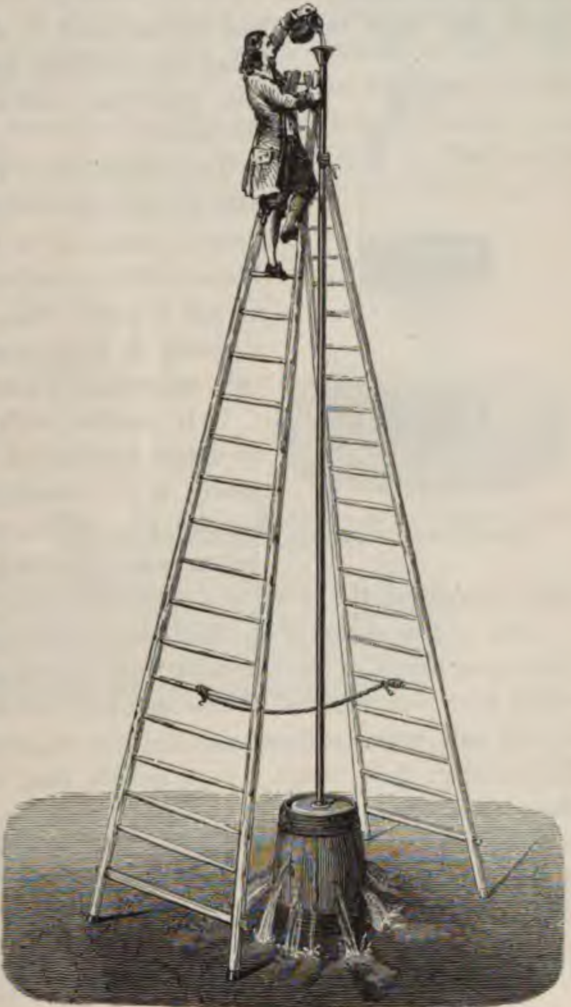

FIG. 45.—Hydrostatic paradox. Pascal's experiment.

as the length of the column of water in the tube. One kilogramme of water can produce, in this manner, the same effect as thousands of kilogrammes.

If, in the same vessel, we introduce liquids of various densities, not susceptible of mixing—for example, mercury, water, and oil—these liquids will range themselves in the order of density. Moreover, when equilibrium is established (Fig. 46), the separating surfaces are plane and horizontal.

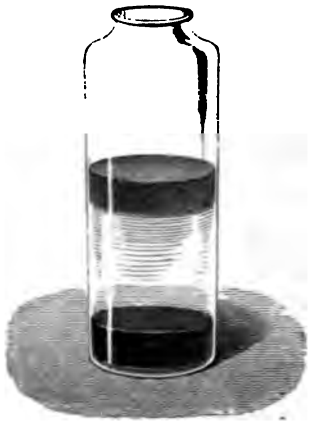
Fig. 46. — Equilibrium of superposed liquids of different densities.

This experimental fact might be foreseen, for the equilibrium of a single liquid insisting upon, as we have before seen, a horizontality of surface, this equilibrium is not broken, when this surface also supports at every point a pressure due to a superposed liquid.

It is possible, with great precautions, to obtain equilibrium with two liquids of nearly equal densities, by placing the heavier one uppermost, but the equilibrium is unstable, and the least agitation again establishes the order of densities.

This is the reason of the existence, in the fiords or gulfs on the Norwegian coasts, of the sheets of fresh water brought by the rivers, which have been observed; these maintain themselves on the surface of the salt water without mixing with it, although sea-water is heavier than fresh water. Vogt records that in one fiord one of these sheets was 1·50m. deep. This phenomenon is only possible in calm localities, as the agitation caused by winds would soon mix the fresh water with the salt. The same fact has been noticed in the Thames, the tides bringing the sea-water to a great distance in the bed of the river.

The equilibrium of a liquid contained in a vessel and submitted to the action of gravity alone is independent of the form of the vessel. Hence this very natural consequence, that a liquid rises to the same height in two or more vessels which communicate one with the other. Experiment shows that the level is always the same in different tubes or vessels connected together by a tube of any form whatever, provided always that the diameter of each be not too small (Fig. 47).

It is this principle which serves as a basis to the theory of artesian wells, the construction of the fountains which play in public or private gardens, and the distribution of water in our towns. We shall return to these interesting applications in another volume. It is the principle only which interests us here. The water which arrives at the orifice of an artesian well often proceeds from very distant reservoirs, forming as it were subterranean rivers, the level of which, at the source, is higher than at the point of outflow. The pressure is thus transmitted to a distance, and the jet which follows would rise precisely to the same height as the original source, were it not for the resistance of the air and the friction to which the ascending column is subject in its passage. The same thing happens with the jets of water fed by a reservoir higher than the basin and communicating with it by subterranean pipes.

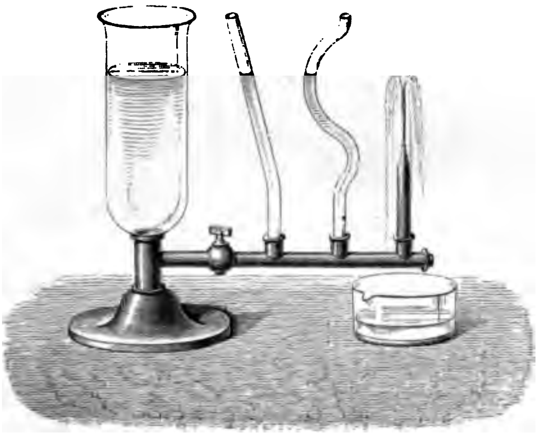

FIG. 47.—Equality of height of the same liquid in communicating vessels.

If two communicating vessels contain liquids of different densities, the heights are no longer equal (Fig. 48).

Let us first try mercury. The level will be established in the two tubes at the same height. In the left-hand tube, let us now pour water. The mercury will rise in the right-hand tube, under the influence of the pressure of the new liquid. Equilibrium having been established, it is easily proved that the heights of the level of the water and of the mercury, measured from their common plane of separation, are in the inverse ratio of their densities. For example, if the mercury rises 3 millimetres, the column of water will have a length of 40·8 millimetres; that is to say, a length 13·6 times greater. Now, a volume of water weighs 13·6 times less than an equal volume of mercury.

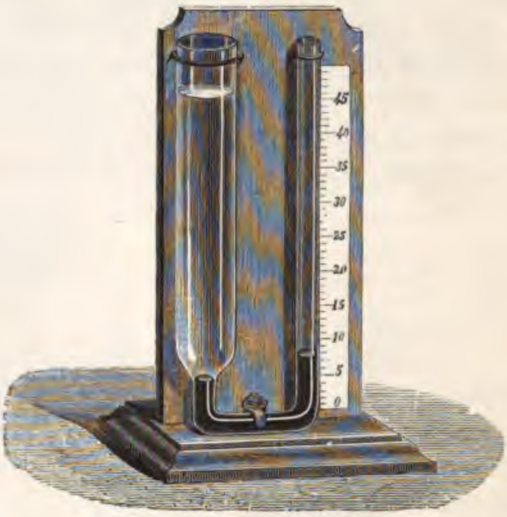

FIG. 48.—Communicating vessels. Heights of two liquids of different densities.

CHAPTER VII.

EQUILIBRIUM OF BODIES IMMERSED IN LIQUIDS.—PRINCIPLE OF ARCHIMEDES.

Pressure or loss of weight of immersed bodies—Principle of Archimedes—Experimental demonstration of this principle—Equilibrium of immersed and floating bodies—Densities of solid and liquid bodies ; Areometers.

EVERYBODY knows that when we immerse in water a substance lighter than itself,—a piece of wood, or cork, for instance,—it requires a certain effort to keep it there. If left to itself, it rises vertically and comes to the surface, where it floats, partly in and partly out of the water.

What is the cause of this well-known phenomenon? The force of gravity. In the air, the same body left to itself falls vertically; in water, the lateral pressures, the downward pressures, and those in the contrary direction, are partly destroyed, and are reduced to a pressure which is exerted in a direction contrary to the force of gravity. We have proved the existence of this pressure in an experiment before described (Fig. 41). It is stated, and experiment confirms the theory, that this pressure is precisely equal to the weight of the liquid displaced. The point of application of this force, which is called the *centre of pressure*, is the centre of gravity of the volume of liquid, the place of which is occupied by the body. The loss of weight of which we speak being greater, for bodies lighter than water, than the weight of the body itself, it is evident that it must cause the body to move in a direction opposite to that which gravity would impose on it; hence the rising of the piece of wood or cork to the surface of the liquid. But this loss occurs also in the case of bodies heavier than water, and in any kind of liquid. Every one knows that it was Archimedes, one of the greatest geometers and physicists of antiquity, who had the glory of discovering this principle, which is known by his name:—

All bodies immersed in a liquid suffer a loss of weight precisely equal to the weight of the displaced liquid.

The experimental demonstration of the principle of Archimedes is made by means of the hydrostatic balance.

Take a hollow cylinder, the capacity of which is exactly equal to the volume of a solid cylinder, so that the latter can exactly fill the former. Both are furnished with hooks, so that the solid cylinder can be placed, with the hollow one above it, below one of the pans of the hydrostatic balance (Fig. 49). This done, the beam is raised by means of rackwork fitted to the column of the balance, high enough to permit a vessel filled with water to be placed beneath the two cylinders, when the beam is horizontal.

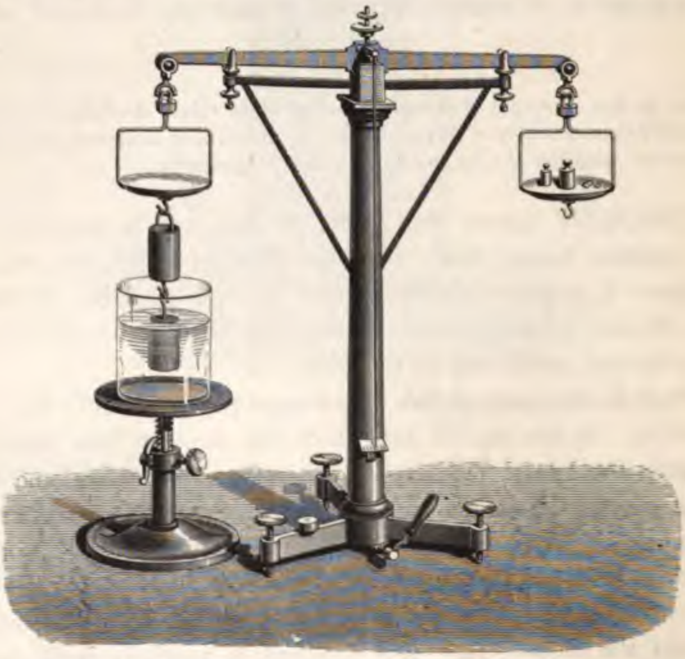

FIG. 49.—Experimental demonstration of the principle of Archimedes.

In this state, equilibrium is established by the aid of a counterpoise in the other scale. If then the beam of the balance is lowered, the solid cylinder is immersed in the water, and equilibrium is disturbed. This alone would suffice to demonstrate the vertical pressure, or the loss of weight of the immersed body. To measure this weight, the solid cylinder itself is placed entirely in the water, and equilibrium is re-established by pouring water slowly into the hollow cylindrical vessel. It will then be seen that the beam will again become horizontal, as soon as the hollow cylinder is quite filled.

Thus the loss of weight is exactly equal to the weight of the water poured in, that is to say, the water displaced by the immersed body. The preceding experiment then fully proves the principle of Archimedes.

How is it then that equilibrium is not disturbed, when, after having exactly balanced a vessel containing liquid and a solid body placed side by side on the plate of a balance, the solid body is immersed in the water? The solid body loses weight, as has been proved. Nevertheless the equilibrium remains. It must be that the vessel and its contents have been increased by an equivalent weight, or that, to put it another way, the water undergoes from above downwards a pressure equal to that at work upwards. That this explanation is correct is proved by the aid of the apparatus above described.

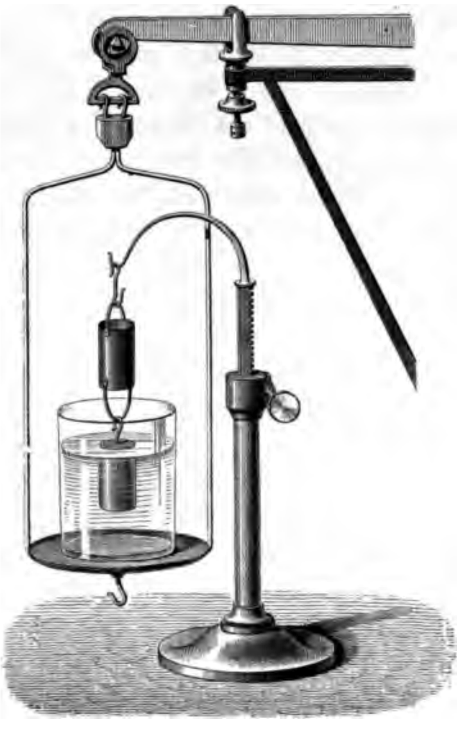

FIG. 50.—Principle of Archimedes. Reaction of one immersed body on the liquid which contains it.

A vessel partly filled with water is weighed. Then the solid cylinder is immersed, supported separately, as is shown in Fig. 50. Equilibrium is disturbed: the beam leans to the side of the vessel. By how much is the weight of the water augmented by the immersion?

Precisely by the weight of the displaced water: as is proved by the fact that, in order to again establish equilibrium, it is sufficient to take from the vessel a volume of water exactly sufficient to fill the hollow cylinder of the same interior capacity as the body immersed.

The principle of Archimedes is of great importance. It enables us to determine the conditions of equilibrium with immersed or floating bodies, to explain numerous hydrostatic phenomena, and to solve a host of problems of great practical interest. For example, it enables us to determine beforehand what must be the form, weight, and distribution of the cargo of ships, in order that stable equilibrium be properly combined with the other qualities of the vessel, such as rapidity, &c.

At each instant we have, in the phenomena which take place in liquids, proofs of the existence of pressure. When we take a bath, if we compare the effort which is necessary to raise one of our limbs to the top of the water with that which it requires in air, we are struck with the difference. Very heavy stones, that we should have great trouble to lift out of water, are moved and lifted with facility when they are immersed in it. Lastly, when we walk into a river which imperceptibly gets deeper, we feel the pressure of our feet on the bottom diminish by degrees, until at last we no longer have any power to walk forward. The weight of our body is nearly counterbalanced by the pressure of the liquid, and we tend to take a horizontal position in consequence of the unstable equilibrium in which we find ourselves.

This brings us to say a few words on the conditions of equilibrium of bodies immersed in liquids or capable of floating on their surface.

It is at once evident that an immersed body cannot be in equilibrium if its weight exceeds that of an equal volume of the liquid. In this case it falls, under the action of the excess of weight over pressure. Neither will it remain in equilibrium if its weight is less than the displaced liquid: in this case it will rise to the surface, urged by the excess of pressure over its weight or over the force of gravity. It is thus that cork, wood—at least certain kinds of wood—wax, and ice, swim on the surface of water, whilst most of the metals, stones, and numerous other substances fall to the bottom. Since mercury is a liquid of great density, most of the metals float on its surface. A leaden ball, a piece of iron, or copper, will not sink in it; gold and platinum, on the contrary, will.

We will now examine the case of a body the specific gravity of which is precisely equal to that of the liquid. If its substance is perfectly homogeneous, the body will remain in equilibrium, in whatever position it is placed, in the middle of the liquid. In this case, the weight and the pressure not only are equal and opposite, but are both applied at the same point; that is to say, the centre of gravity and the centre of pressure coincide.

Fish rise and fall, at will, in water. These different movements are rendered possible by the faculty these creatures have of compressing or expanding a sort of elastic bag filled with air, situated in the abdomen. According to the volume of the swimming-bladder—that is the name of the organ—the body of the fish is sometimes lighter and sometimes heavier than the volume of water which it displaces: in the first case it rises, in the second it descends. M. Delaunay quotes, in his Course of Physics, a very curious phenomenon which is very easily explained by the principle of Archimedes. "When," he says, "a grape is introduced into a glass full of champagne, it immediately falls to the bottom. But the carbonic acid, which continually escapes from the liquid, soon forms many little bubbles round it. These bubbles of gas add, so to speak, to the bulk of the grape, increase its volume, without its weight being sensibly augmented: the pressure of the liquid, which was at first less than the weight of the grape, soon becomes greater than this weight, and the grape rises to the surface of the liquid. If, then, we give a little jerk to the grape, and detach from it the bubbles of carbonic acid which adhere to its surface, it again descends to the bottom of the glass, after a short time to remount. The experiment may thus be continued as long as any carbonic acid escapes."

If the immersed body is not homogeneous,—if, for example, it is made of cork and lead, the substances having been combined in such a manner as to weigh together as much as the displaced water (Fig. 51), without having a common centre of gravity, the centre of gravity of the whole and the centre of pressure no longer coincide. To establish equilibrium these two points must be in the same vertical plane, as in the positions 1 and 2, or otherwise equilibrium will be unstable, if, as in 2, the centre of gravity is uppermost. In position 3, this condition not being realized, equilibrium will only take place when the oscillations of the body bring it to the first position.

When a body displaces a volume of liquid, the weight of which is greater than its own, either in consequence of its real volume or of its form, it floats on the surface.

In this case, the weight of the water which the portion immersed displaces is precisely that of the body and the load which it supports: thus a ship, with its cargo of men, materials, and merchandise, weighs altogether just as much as the volume of the sea-water displaced.

Moreover, the second condition of equilibrium is still the same; that is to say, the centre of gravity of the body and the centre of pressure must be on the same vertical line. But it is no longer indispensable to stability, that the first point be below the other. Besides, according to the position and the form of the floating body, the form of the displaced volume itself changes, and the centre of pressure changes with it, so that at each instant the conditions of equilibrium vary.

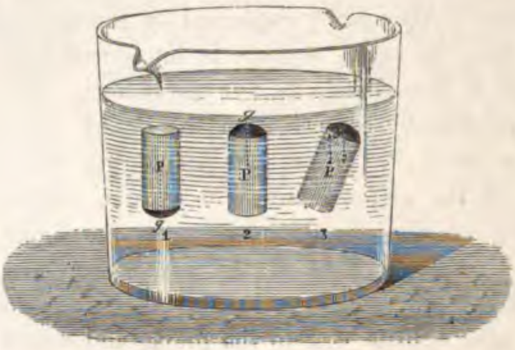

FIG. 51.—Equilibrium of a body immersed in a liquid of the same density as its own.

In ships, perfect equilibrium never exactly exists, even when the sea is smooth and calm. Oscillations of greater or lesser amplitude are always taking place; the principal point to attain is that, under the most unfavourable circumstances, the movements of the vessel shall not be decided enough to upset it.

The principle of Archimedes is of the greatest use in science, in determining the specific gravity of liquid or solid bodies. Let us briefly indicate the methods adopted for this determination.

Let us remember that the specific gravity of a body is the relation which exists between its weight and that of an equal volume of pure water taken at a temperature of 4 degrees centigrade. How can we find the number which expresses the specific gravity of a body? First, we must obtain its weight: for this the balance is used. Secondly, we must know the weight of an equal volume of water: the operations necessary for this determination will be described in the sequel. These two numbers obtained, the quotient, the first divided by the second, gives the specific gravity.

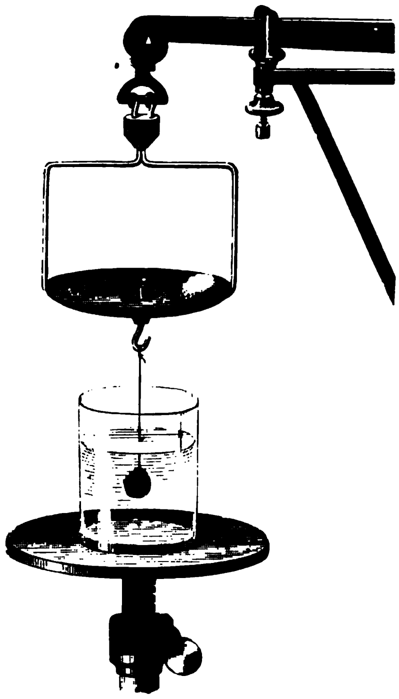

Fig. 52.—Density of solid bodies. Method of the hydrostatic balance.

The only difficulty is then to find the weight of a volume of water equal to that of the body. We will explain the three methods employed. Let us take the case of a piece of iron weighing in the air 246·5 gr. It is suspended by a very fine cord to one of the plates of the hydrostatic balance, and to establish equilibrium a counterpoise is placed in the other plate. Then the balance is lowered until the piece of iron is immersed in the water (Fig. 52). At this moment the beam falls on the side of the tare, and it is necessary to put weights equal to 31·65 gr. in the plate which holds the body, to re-establish equilibrium. These weights represent the displaced water. On dividing 246·5 by 31·65, 7·788 is found to be the specific gravity of the iron, which shows that for equal volumes the iron weighs 7 and 788 thousandths times as much as water. We now come to the second method.

Fig. 53 represents an instrument called an areometer,[1] which was invented by the physicist Charles, although it is generally attributed to Nicholson; it is constructed so that when placed in water the liquid is precisely level with a standard point on its upper rod, when the pan which surmounts this rod is charged with a known weight, let us say 100 grammes. We place the body whose specific gravity is sought for in the little pan at the top, and standard weights are added to obtain the level. If, for instance, 35·8 gr. have been added, the difference, 64·2 gr., of this last weight and the 100 grammes evidently gives the weight of the body in air.

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[1] From the Greek *ἄραιος*, right, and *μέτρον*, measure. Areometers were first used to determine the densities of liquids, as we shall see further on.

From what has been said it will be seen that the areometer is a true balance.

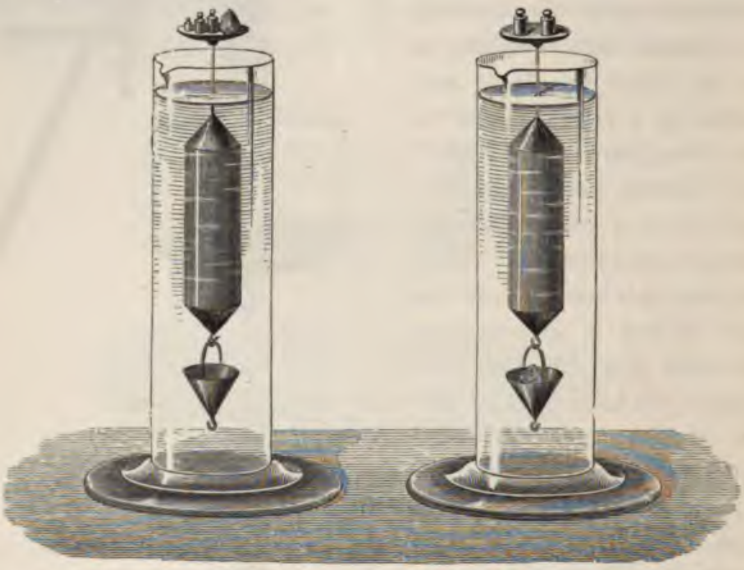

FIG. 53.—Density of solid bodies. Areometer of Charles or Nicholson.

The body is next taken out of the upper pan, and is placed in the little vessel suspended under the instrument: it loses some of its weight, so that the areometer rises, and more standard weights must be added to bring it again to the level: let us suppose 31 grammes added—this is the weight of a volume of water equal to that of the body. Dividing 64·2 by 31, we find 2·07 the ratio sought (the specific gravity of sulphur).

In the case where the body is lighter than water, the small basket is reversed over it, and the body, which pressure causes to rise, meeting with an obstacle, still remains immersed.

A third method to determine the specific gravities of bodies is that of the "specific gravity bottle." Placed in the pan of a balance is the fragment of a body the weight of which is known, but of which the specific gravity is sought, and, by its side, a flask exactly filled with water and well stopped by means of a ground stopper (Fig. 54). Equilibrium is obtained by standard weights. The body is then introduced into the flask, which is again stopped, care having been taken to push the stopper to the same level. A certain quantity of water has come out, the volume of which is precisely equal to that of the body which takes its place. After having well dried the flask, it is replaced in the pan of the balance, and the weights required to restore equilibrium give the weight of the water expelled. Having the weights of equal volumes of the substance and of water,

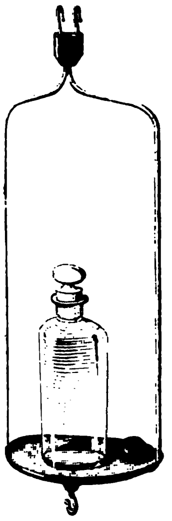

FIG. 54.—Density of solid bodies. Method of the specific gravity bottle.

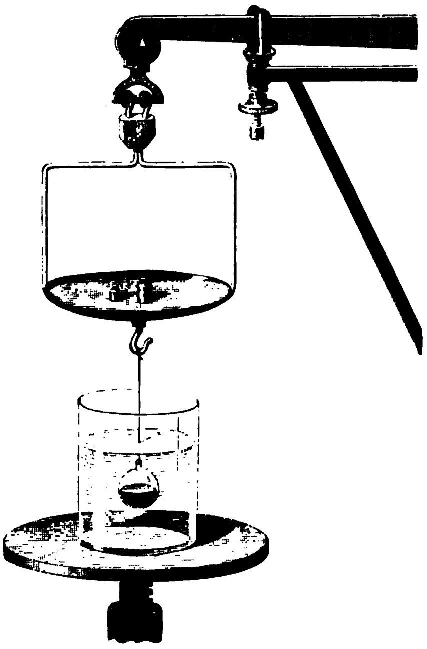

FIG. 55.—Density of liquids. Hydrostatic balance.

its specific gravity is easily determined. This process is not an application of the principle of Archimedes, like the first two.

These three methods require some precautions; the body immersed in the water retains, adhering to its surface, air-bubbles which must be removed. If the body easily absorbs water, or even dissolves in it, another liquid is used—oil, for example—in which case we must determine the density of the body relatively to the oil, to that of water, which presents no difficulty.

The specific gravity of liquids is determined by processes analogous to those we have just described. A hollow glass ball, ballasted so that it is heavier than the liquids to be weighed, is hooked under the pan of the hydrostatic balance (Fig. 55).

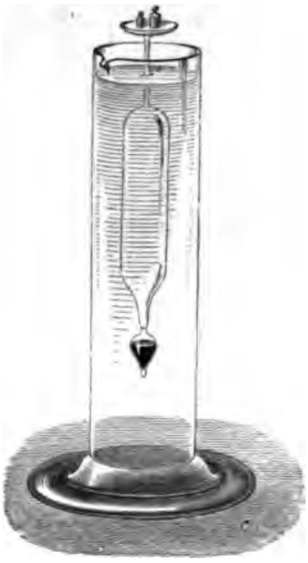

FIG. 56.—Specific gravity of liquids. Fahrenheit's Areometer.

FIG. 57.—Specific gravity of liquids. Method of the specific gravity bottle.

Weighed in air and then in water, the difference of the weights gives the weight of a volume of water equal to its own. Well dried and weighed in the liquid of which the specific gravity is wanted, this second difference gives the weight of an equal volume of the liquid. Dividing the latter by the former, the quotient is the specific gravity sought. Fahrenheit's areometer (Fig. 56), immersed in water, requires a given weight to be placed on it, so that a fixed standard point on its rod is level with the surface of the liquid. It is clear that this additional weight, together with that of the instrument, marks the weight of the volume of water displaced. Immersed in another liquid, in oil for example, we obtain in the same way the weight of a volume of oil equal to the volume of water. The division of the second weight by the first gives the specific gravity of the oil. Lastly, with a flask terminated by a straight tube (Fig. 57), which is successively filled with water and some other liquid as far as the standard mark on the stem, the weight of the two equal volumes of water and the liquid is found, and thence the specific gravity.

We give, to terminate this chapter, a table of the specific gravities of some of the most common solid and liquid bodies. As we shall soon see, the volumes of the bodies vary according to the degree of temperature at which they are determined. These variations do not affect their weight, but precisely on that account the specific gravity of the body is variable. It has therefore been necessary to reduce them to a constant temperature. For water only, this temperature is 4° C.; for all the other solid and liquid substances, it is convenient to take that of melting ice, or 0° C.

SPECIFIC GRAVITIES OF DIFFERENT BODIES AT 0° C.

SOLIDS.

Metals.		Minerals, Rocks, &c.		Vegetables, &c.	
Rolled platinum	22·06	Diamond	3·53	Boxwood	1·32
Cast gold	19·26	Marble	2·65 to 2·84	Heart of oak	1·17
Cast lead	11·35	Granite	2·75	Black ebony	1·19
Cast silver	10·47	Sandstone	2·60	Oak	0·91
Drawn copper wire	8·95	Quartz	2·65	Beech	0·75
Cast ditto	8·85	Glass	2·50	Willow	0·49
Iron	7·79	Porcelain	2·24	Poplar	0·39
Tin	7·29	Sulphur	2·08	Cork	0·24
Aluminium	2·67	Ice at 0°	0·93	Elder pith	0·08

LIQUIDS.

Mercury	13·596	Water at 0°	0·9998	Olive oil	0·915
Bromine	2·966	Sea-water	1·026	Essence of turpentine	0·865
Concentrated sulphuric acid	1·841	Milk	1·03	Alcohol	0·792
Nitric acid	1·520	Bordeaux	0·994	Sulphuric ether	0·736
Water at 4°	1·000	Burgundy	0·991		

CHAPTER VIII.

WEIGHT OF THE AIR AND OF GASES.—THE BAROMETER.

The air a heavy body—Elasticity and compressibility of air and other gases—Pneumatic or fire syringe—Discovery made by Florentine workmen—Nature abhors a vacuum—Experiments of Torricelli and Pascal—Invention of the barometer—Description of the principal barometers.

WE live at the bottom of a fluid ocean, the mean depth of which is at least a hundred times greater than that of the seas, and which envelopes all portions of the terrestrial spheroid. The substance of which this ocean is formed is the air, a mixture of various other gases, the two principal ones being oxygen and nitrogen: carbonic acid gas, aqueous vapour, sometimes ammonia, are also found, but in variable proportions, whilst the two gases first named are everywhere found in the same proportion—a proportion such that, by volume in 100 parts, 21 are oxygen and 79 nitrogen.

Air is, as is well known, the indispensable aliment to the respiration of animals; those even which habitually live in water cannot do without it; it is not less necessary to the vegetable world, which, under the influence of light, decomposes the carbonic acid in the air, fixes the carbon and liberates the oxygen, which is absorbed, on the contrary, in animal respiration.

The transparency of the air itself is so great that it does not present itself to the sight, at least when we are dealing with a small thickness. But in the case of great distances the interposition of gaseous strata is very perceptible; it is these which give to distant bodies, such for example as mountains bounding the horizon, a bluish tint, which tint, very brilliant and pure, forms the colour of the sky, when the atmosphere is cloudless. Were it not for the blue colour of the atmosphere, the sky would be colourless, that is, entirely black; and the stars would then stand out brightly in broad day. During the night, the aërial envelope, being no longer lighted up by the rays of the sun, but only by the feeble light of the moon and stars, appears of a dark blue; and, if in the day we observe it from a very high mountain, the same appearance is produced—a thinner stratum of the air, which moreover is less dense in the higher regions, absorbing but a slight portion of the blue rays of the solar light.

The existence of air is, moreover, revealed to us by other phenomena, which act upon us through the medium of the organs of hearing and touch. When the air is still, it is only necessary for us to move in order to feel its presence. The mass of air resists the displacement which we cause in it, and the resistance is sensible to our hands or our face. But the material nature of the air is manifested still more perceptibly by the movements with which it is itself animated; from the lightest breeze to the most violent winds, hurricanes, and tempests, all atmospheric agitations are continual proofs of its existence.

Lastly, it is in consequence of the vibrations communicated to the air by sonorous bodies that sound is propagated to our ear. The air itself, when it is put in vibration under favourable conditions, becomes a producer of sound, as we shall see further on. Most of the properties of air have been utilized, and we shall, in the sequel, describe numerous and very interesting applications. The object of this chapter, meanwhile, is the study of the properties of air considered as a body which has weight; and of those phenomena due to the weight of air or other gaseous substances. That air has weight is easily proved by a very simple experiment.

We shall shortly describe the instrument which is used to exhaust from a vessel or receiver the air which it contains—to make a vacuum, as physicists say. This is called an air-pump. Now, if we take a hollow glass globe fitted with a metallic neck furnished with a stopcock, and weigh it after having made a vacuum (Fig. 58), we have only to open the cock and allow the air to enter, to see that the beam of the balance leans then to the side of the ball. To re-establish the interrupted equilibrium, weight must be added—about 1·29 grammes for each litre that the globe holds.

Thus then is the weight of the air directly demonstrated. The same experiment, made with other gases, proves in the same manner that bodies in a gaseous state, like liquids and solids, obey the action of gravity. Galileo first suspected and enunciated the important truth that air is heavy; but the experiment we have just indicated is due to Otto de Guericke, the inventor of the air-pump.

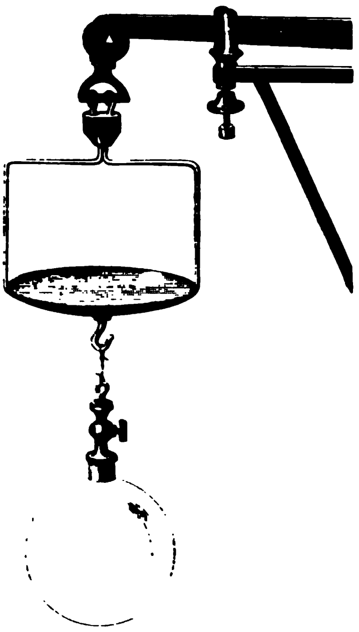

FIG. 58.—Experimental demonstration of the weight of air and other gases.

If the air contained in a vessel is heavy, that is, if its weight is susceptible of being valued by means of a balance, the immense volume of air which rests on the surface of the earth must press on it in proportion to its mass, and this pressure, which is doubtless enormous, must be manifested in some way. This is indeed what happens; but, before studying these phenomena, let us say a few words on the properties of gases, both those which they possess in common with liquids, and those which characterize them in a special manner.

Like liquids, gases are formed of particles—molecules—which glide one over the other with extreme facility. Thus we see gaseous masses give way to the least force—dividing themselves, and allowing all the movements of solid and liquid bodies to continue in their midst, and not opposing them with sensible resistance, until the velocity and displacement of their molecules become considerable.

Gases are eminently elastic and expansible. Let us take a flattened and compressed bladder, only enclosing a small volume of air in comparison with the quantity which the same bladder when filled out would hold (Fig. 59). In this state, the interior air does not increase in volume, because the elastic force with which its molecules are endowed, and which we are about to demonstrate, is balanced by the pressure of the exterior air. Let us place this bladder under the receiver of an air-pump. In proportion as the vacuum point is approached, one sees the bladder increase in volume; it swells out, and may even burst under the interior pressure which distends its walls. Let the air again into the receiver—it immediately returns to its primitive volume; which proves at once that air—and any other gas would conduct itself in the same manner—is elastic and compressible.

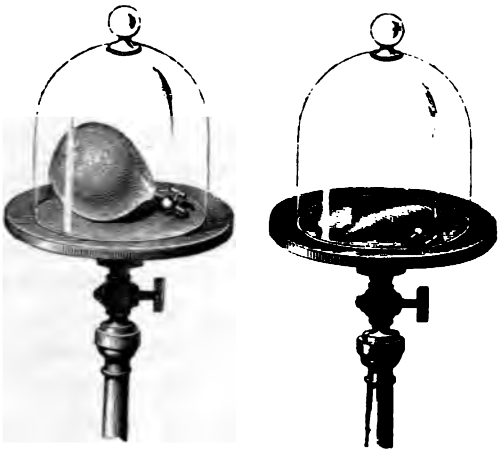

FIG. 59.—Elasticity and compressibility of gases.

These two properties are also proved by the aid of the fire-syringe. By forcing a well-fitted and greased piston into a glass tube filled with air (Fig. 60), we experience a slight but increasing resistance, and the volume of the air diminishes one-half, two-thirds, &c. This first operation proves the great compressibility of gases. Now the piston, arrived at the end of its course and abandoned to itself, returns spontaneously to its original position—a proof no less evident of the elasticity of the air.

As compression produces heat, this instrument may be used to light a piece of tinder placed under the piston; but in this case the compression must be very rapid. Hence the name given to the instrument. Gases then, like liquids, are elastic and compressible; but whilst this latter property is very slight in liquids, it is, on the contrary, very considerable in the case of gases. Let us also note that if liquid molecules have a cohesion nearly *nil*, in gases the molecules have a tendency to repel each other, which is only counterbalanced by pressure from without. Hence it follows that when this pressure diminishes, the volume of the gas increases; in liquids the volume remains constant, at least as long as the body retains the same state.

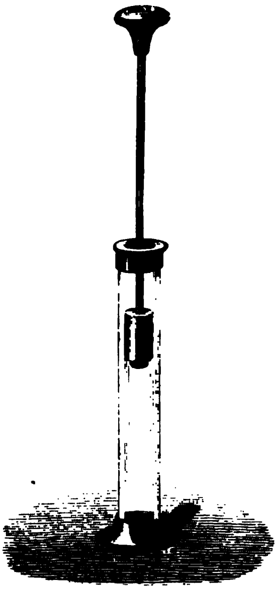
FIG. 60.—Pneumatic syringe.

Lastly, a property which again distinguishes liquids from gases, is the very feeble comparative density of these latter; whilst the weight of a litre of liquid may be as high as 13596 grammes (the weight of a litre of mercury) and is never lower than 715 grammes (ether), the weight of a litre of gas or vapour never exceeds 20 grammes and may be as low as 9 centigrammes. Moreover, in gases, as in liquids, the principles of equality of pressure and of equality of transmission of pressure in every direction, are indicated by theory and verified by experiment; we shall have occasion soon to give some examples of this. We will now return to the phenomena due to the weight of the air.

We have seen that Galileo was the first who suspected this weight. The history of this important discovery is well known. It was made in 1640. Some Florentine workmen, ordered to construct a pump in the palace of the Grand Duke, were greatly astonished that the water, in spite of the good condition into which they had put the instrument, would not rise to the upper extremity of the pipe of the body of the pump, that is to say, beyond 32 Roman feet (about 10·3m.). The learned men—engineers and Florentine academicians—being consulted on this anomaly, did not know what to answer. They addressed themselves to Galileo, then aged seventy-six years, whose immense reputation had not been shaken by persecutions. Galileo at first gave an evasive answer, but the question made him reflect; he thought that the pressure of the air was the cause which made the water rise as far as this height, and that "Nature's abhorrence of a vacuum" was an idle explanation, since it must be then supposed that this abhorrence would not manifest itself beyond a given height. He first proved the weight of the air by weighing a bottle, the air of which had been expelled by the vapour caused by the ebullition of a certain quantity of water. But he left to his disciple Torricelli the care of extending the verification of his conjectures.

A year after the death of Galileo, it occurred to Torricelli to examine how mercury, a liquid denser than water, would act *in vacuo*.

He took a long tube closed at one end, which he filled with this liquid; then, covering the open end of the tube with his finger, in such a way as to prevent the liquid from falling out and the air from getting in, he plunged this extremity into a vessel full of mercury; then, leaving the liquid to itself, he held the tube in a vertical position (Figs. 61 and 62). Torricelli then saw the liquid descend from the top, and, after a few oscillations, settle itself at a level which remained nearly invariable at 28 Roman inches (76 centimetres) above the level of the mercury in the vessel.

If Galileo's idea was right, and the column of water of 32 feet was really maintained by the pressure of the atmosphere, the same pressure would raise the mercury, being thirteen times and a half heavier than water, to a height thirteen times and a half less. Now, 28 inches are thirteen and a half times less than 32 feet!

Such is, in its simplicity, this grand discovery. Such is Torricelli's tube, or, as it is now called, the *barometer*, an instrument used to measure the pressure of the atmosphere. It was not without opposition that the explanation of Torricelli on the elevation of water and mercury was accepted by the scientific men of his day. But additional experiments suggested by Pascal left no doubt. Pascal remarked that if the weight of the air were really the cause of the observed phenomena, the pressure ought to be less in proportion as the barometer was observed at a greater height in the atmosphere, as the superposed gaseous column above the exterior liquid would be less. The height of the mercury in Torricelli's tube ought then to be smaller at the top of a mountain than in the plain. Hence the famous experiments which he made with Périer, his brother-in-law, on the Puy-de-Dôme, and those which he executed himself at the base and at the top of the tower of Jacques la Boucherie. The results were in every point conformable to the inferences drawn from the new theory.[1]

The height of the mercury in Torricelli's tube is independent of its diameter, provided always that this diameter be not too small:

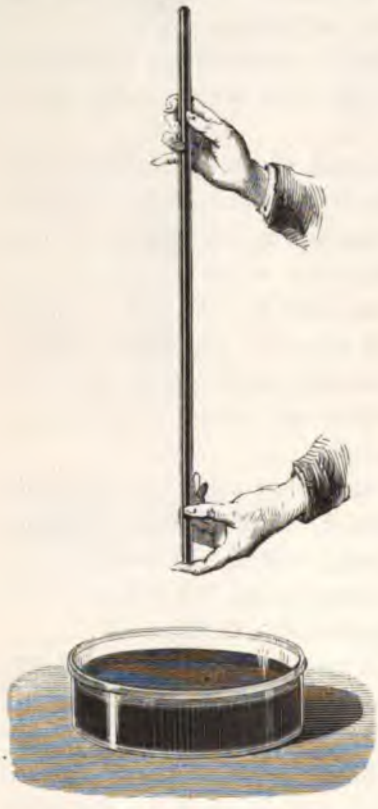

FIG. 61.—Torricelli's experiment.

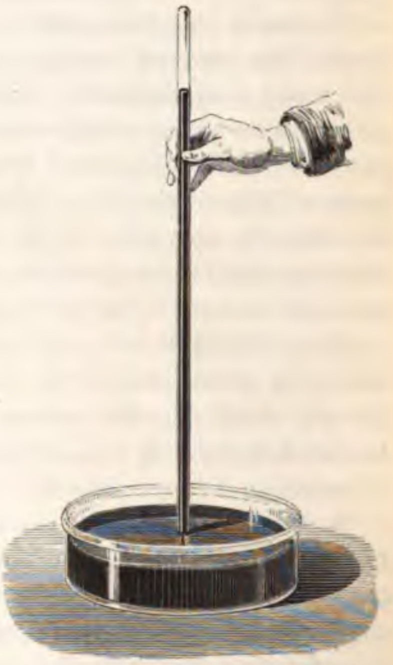

FIG. 62.—Torricelli's experiment. Effect of the weight of the atmosphere.

for then, other forces which we shall study subsequently have a great influence on the level of the liquid. This fact is a very natural consequence of the equal transmission of pressure in liquids: the column of mercury acts by its weight on all the mercury in the trough, so that each element of surface equal to the section of the tube is pressed equally by this weight. And as there is equilibrium, it follows that the pressure of air on this same unit of surface is precisely equal to the pressure of the mercury.

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[1] "I have thought," wrote Pascal to Périer, "of an experiment which will remove all doubt, if it be executed with exactness. The experiment should be made *in vacuo* several times, in one day, with the same quicksilver, at the bottom and at the top of the mountain of Puy, which is near our town of Clermont. If, as I anticipate, the height of the quicksilver be less at top than at the base, it will follow that the weight or pressure of the air is the cause of this; there certainly is more air to press at the foot of the mountain than at its summit, while one cannot say that Nature abhors a vacuum in one place more than in another."

What must we conclude from this? That the mass of the atmosphere presses on the earth's surface, as if this surface were everywhere covered with a stratum of mercury about 76 centimetres thick. Let us add, that the pressure in the air being transmitted equally and in every direction, the weight of the atmosphere makes itself felt wherever the air penetrates and by whatever remains in communication with it, as in the interior of houses, in cavities, and on the surface of bodies. This explains why all bodies situated on the earth's surface are not crushed by this enormous pressure, which is not less than 10,333 kilogrammes (about 10 tons) on the average on each square metre of surface. The surface of the human body being nearly a square metre and a half in a person of average height and size, each of us always supports a load which is about equal to 15,500 kilogrammes (nearly 15 tons). We have just given the reason why this load does not crush us: all the pressures exercised on every part of our body and from within produce equilibrium.

But at first sight it seems incomprehensible that we are not ground to dust under the effect of these contrary pressures. The reason is very simple. All the fluids contained in our organism act against the pressure of the atmosphere, and it is this constant reaction which explains our insensibility to pressure, and the absence of the phenomena which the pressure of the air would cause, as at first supposed. This reaction is not a simple hypothesis, as the process of "cupping" proves. "Cups" are small vessels of metal or glass, which are applied to the skin: a vacuum being made inside them, the skin swells up, the small veins burst, and the blood flows out, because it is no longer maintained in the veins by atmospheric pressure.

In the various courses of physics, some interesting experiments are introduced to show the energy of atmospheric pressure. These we will rapidly describe.

One of the first known is that of the Magdeburg hemispheres: it is attributed to Otto de Guericke.

Two copper hemispheres fitting one into the other, in such a way as to form a hollow sphere, are fixed by a stopcock to the pipe of the air-pump (Fig. 63). While they are full of air, the slightest effort is sufficient to separate them. But when a vacuum is made in the interior of the sphere, it requires a considerable effort to effect the separation. This is easy to account for, since the pressure on two hemispheres of only 2 decimetres (about 4 inches) in diameter, is 324 kilogrammes (about 6 cwts.) on each of them.

In one of his experiments, the illustrious burgomaster of Magdeburg caused each hemisphere to be pulled by four strong horses without being able to separate them; the diameter of the hemispheres being 65 centimetres, the pressure was 3,428 kilogrammes. The total pressure on the hemispheres is greater even than this; but here, it is only a question of that which is exerted in the direction of resistance, which equals on either side the pressure on a circle of the same diameter as the sphere.

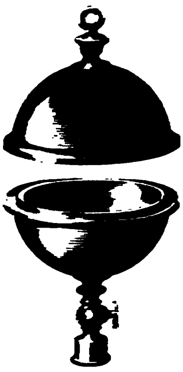

FIG. 63.—Magdeburg hemispheres.

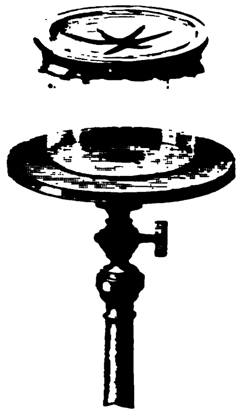

FIG. 64.—Bursting a bladder by exhausting the air underneath it.

Another experiment consists in making a vacuum in a vessel, over the mouth of which a bladder has been stretched, which prevents the air from getting in. As the vacuum point is approached, the membrane is depressed under the weight of the exterior air, and at last it bursts (Fig. 64), a loud detonation similar to that of a pistol-shot accompanying the rupture; this detonation is evidently owing to the sudden entrance of the air into the cavity of the vessel. An apple applied to the end of a thin metallic tube, in the interior of which a vacuum is made, being pressed by the weight of the atmosphere, is cut by the edges of the tube, and a part thus penetrates into the interior.

Lastly, there is a curious experiment which demonstrates the pressure of the air on the surface of liquids. A cylindrical glass bell jar, mounted on a metallic stand, is furnished with a tube and stopcock, which allows of its being screwed on to the air-pump, and a vacuum being made in its interior. When the vacuum is made, the lower end of the tube is immersed in a basin filled with water, and the tap is turned, which opens the communication between the interior of the vessel and the liquid. The atmospheric pressure which is exerted on the water in the basin causes a jet which strikes the top of the bell jar (Fig. 65).

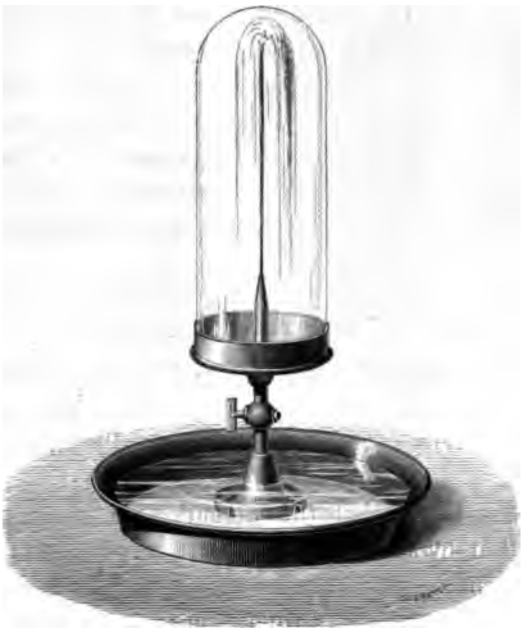

FIG. 65.—Jet of water *in vacuo*.

In what has preceded, we have supposed that the weight of the column of air was the only cause of the atmospheric pressure; that this pressure was constant; and that it was equivalent, on a given surface, to the weight of a column of water of 32 feet, or 10·33 metres, or to that of a column of mercury of 30 inches, or 76 centimetres, having the same sectional area. But experiment proves that this pressure is subject to variations, even in the same place. Further on, we shall study these variations in their relation to meteorological phenomena; but for this purpose we must possess an instrument which indicates them. This instrument, which in principle is no other than Torricelli's tube, and which is called a barometer, deserves a detailed description. It has been differently arranged according to the use to which it is destined, and with the object of rendering its indications precise.

The most simple and at the same time the most exact barometer is nothing more than a tube of glass, which is chosen straight, regularly cylindrical and perfectly homogeneous, of a diameter about three-quarters of an inch, or 2 or 3 centimetres. It is immersed, after having been filled with mercury, in a trough filled with the same liquid.

The trough and the tube are fixed against a vertical support, and remain in the place where the observations are to be made. It is nothing more, as is seen, than a Torricelli's tube. But to properly arrange it, various precautions must be taken, the importance of which is very obvious, and which are equally necessary for the construction of other barometers.

Thus, it is essential that the mercury used be of great purity. This is arrived at by acting upon oxide of mercury with nitric acid; and great care must especially be taken that it does not contain air-bubbles, as their lightness would cause them to rise along the sides of the tube into the vacuum, which is called the Torricellian vacuum. Aqueous vapour and air, being elastic gases, would press the upper level of the mercury, so that its height would not indicate merely the pressure of the atmosphere. To effect this, the tube must be dried and perfectly cleaned before filling it. Once filled with mercury, the liquid is boiled over some burning charcoal, until all the air-bubbles which it contains are expelled. At this moment the aspect of the mercury should resemble a bright mirror; the bright and metallic lustre with which it shines indicates a perfect purity, indispensable for the present purpose.

The large diameter of the tube which forms the *standard* or *normal barometer* possesses this advantage over smaller ones, that it gives a level to the mercurial column which is not altered by the molecular force called capillarity. In this instrument, in order to obtain the height of the barometer, it is sufficient to measure the vertical distance which separates the upper level from that of the mercury in the trough. This is done with a special instrument called a cathetometer, which is composed essentially of a divided scale on which a horizontal glass vernier moves.

There may be seen on Fig. 66, which represents a standard barometer, a double screw fixed to the trough. The lower end should be on a level with the mercury, which is easily accomplished by means of the screw, and it is the distance from the upper point of this screw—which the draughtsman has forgotten to figure—to the upper level of the mercury in the tube which the cathetometer gives. By adding to it the constant length of the screw, we have the height, or the atmospheric pressure sought for.

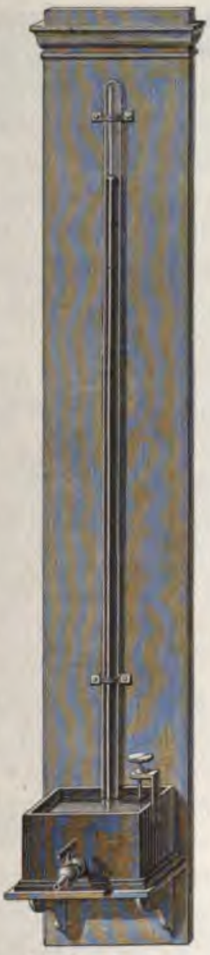
FIG. 66.—Normal or standard barometer.

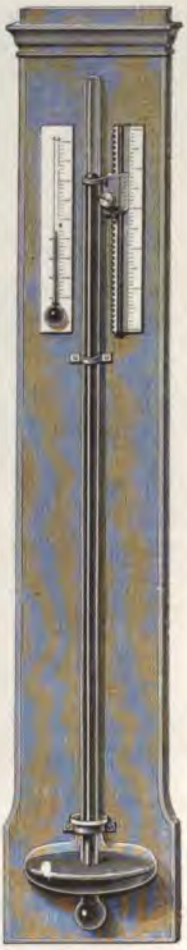
FIG. 67.—An ordinary cistern barometer.

The cistern barometer is distinguished from the preceding one by having a glass cistern into which the tube is inserted (Fig. 67); possessing a large surface, the level of the mercury in it may be considered as constant. The stand on which the instrument is fixed is furnished with a graduated scale, on which slides a moveable index placed in such a way that its upper edge is on a level with the surface of the mercury. The zero of the scale being by hypothesis the level of the mercury in the cistern, the reading of the height is made at once on the scale. Lastly, the scale is furnished with a vernier, which gives the fractions of millimetres or inches. The arrangement which renders this instrument less perfect than the preceding, is that the level of the cistern or the zero of the scale is supposed to be constant; whereas under the influence of the variations of temperature the glass and the mercury expand, and this produces variations in the position of the zero point. Frequently, after a time, these accidental variations produce a permanent alteration, and the scale has to be rectified.

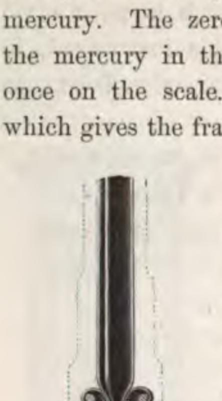
FIG. 68.—Cistern of Fortin's barometer.

The barometers suggested by Fortin, Gay-Lussac, and Bunten are not liable to these inconveniences. But as they are principally constructed with the object of being easily transported, the diameter of the tube is smaller than in a standard barometer, so that capillarity depresses the upper level of the mercury. The observations made with these instruments require therefore a correction to free the readings from this error. But in Gay-Lussac's barometers and those of Bunten, as in the standard barometer, the height is measured by two corresponding scales at the two levels of the liquid, so that the difference, with all corrections made, gives the real atmospheric pressure. In that of Fortin, the zero point is maintained constant by an ingenious contrivance which will be easily comprehended from Fig. 68.

We have a section of the cylindrical cistern which encloses the mercury in which the slender part of the tube is immersed. The upper part of the cylinder is of glass, and shows the level of the liquid. A metallic point in the interior indicates the position of the zero of the scale and the level the mercury ought to attain every time an observation has to be made. As the mercury rests on a bag of impermeable leather connected with the lower walls of the cistern, and as the metallic base is traversed by a screw, the end of which presses against the elastic bag, it follows that we can at will raise or depress the bottom of the liquid, or, what is the same thing, raise or depress its surface, and thus obtain the level required. For travelling, in order that the movements of the mercury may not break the tube, the screw is raised, until the cistern

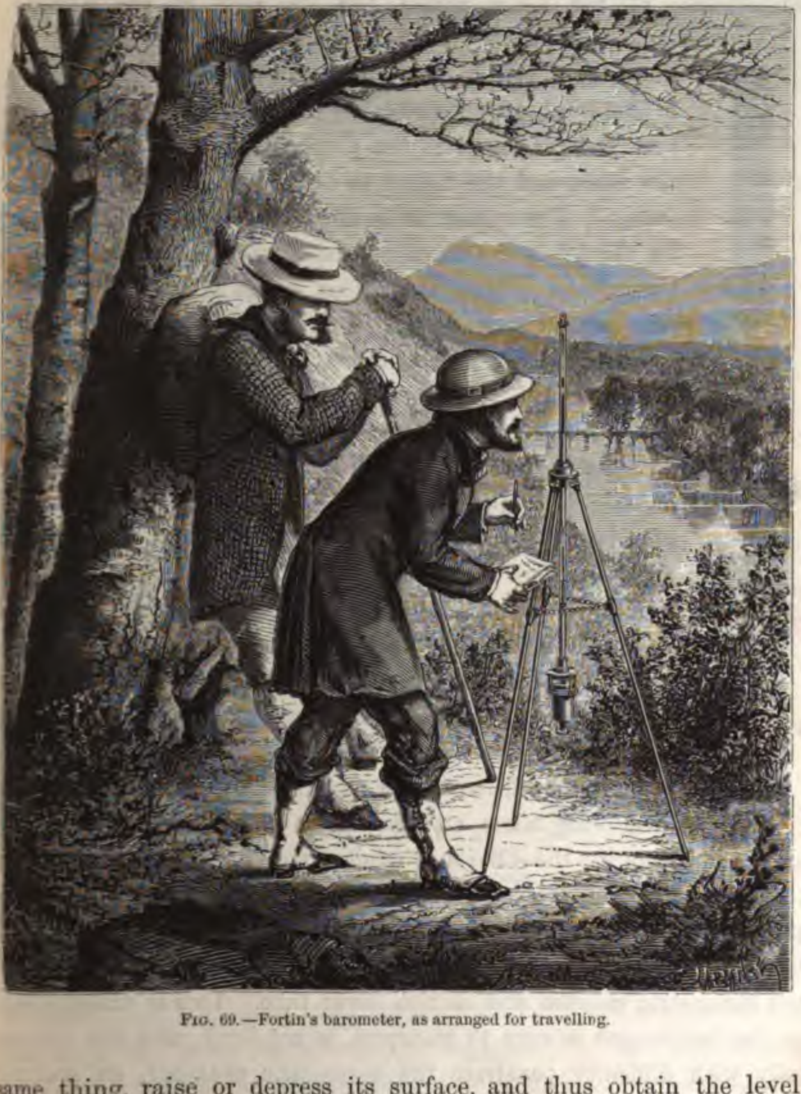

FIG. 69.—Fortin's barometer, as arranged for travelling.

the needle is fixed. The needle turns in either direction, according as the surface of the liquid rises or falls; the dial is divided by comparing it with a fixed barometer. We shall see further on what is signified by the weather indications which we are accustomed to see written against the different divisions of the dial.

For many years metallic or aneroid barometers have been substituted with advantage for these instruments, the indications of which are only of inferior precision. These are based on the elasticity and the flexion of metals formed into thin plates. A flattened brass tube, the section of which is elliptical, is exhausted of air and carefully closed (Fig. 72). It is curved in the form of an arc of a circle, and fixed at its middle point, so that the disengaged extremities of the two halves of the tube can oscillate on either side this fixed point. When the barometric pressure increases, the pressure flattens the tube, which effect causes the curvature of the two arcs to augment, and their free extremities approach each other; the opposite takes place if the pressure diminishes. The disengaged extremities of the tube are connected with levers which move the axis of a cogged sector. The needle of the dial, which is connected by a pinion to this sector, moves either in one direction or the other, and in this manner traverses the divisions on the dial, which are engraved by comparison with a standard barometer.

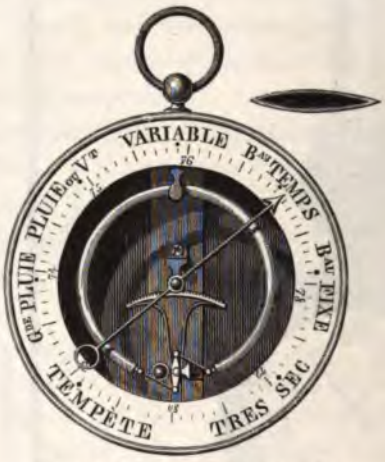

Fig. 72. Bourdon's aneroid barometer.

In the aneroid represented in Fig. 73, the pressure of the air is exerted on the corrugated top of a metallic drum, the interior of which has been exhausted of air. When the pressure augments, this top sinks down; it rises, on the contrary, if the pressure diminishes, and its movements are transmitted to a needle by a peculiar mechanism, the detailed description of which would here be superfluous.

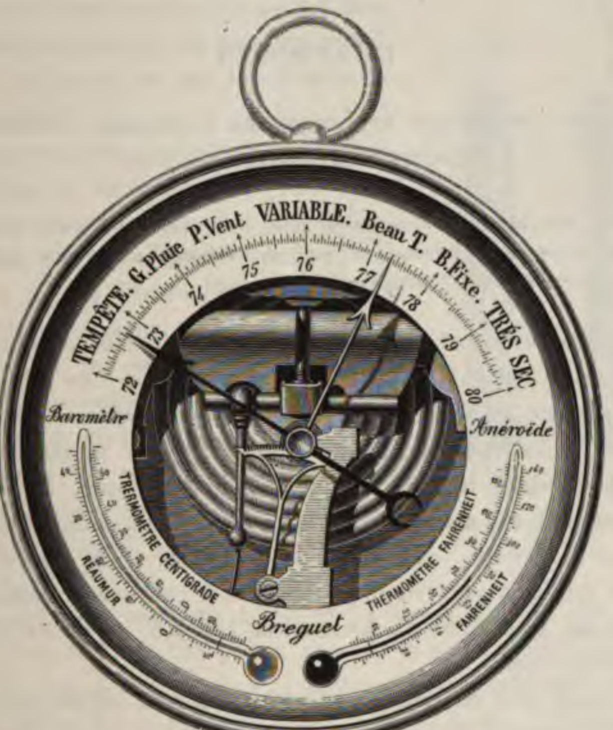

FIG. 73.—Vidi's aneroid barometer.

The invention of this barometer is due to M. Vidi. It has been recently perfected by an English optician, Mr. Cooke.

This kind of barometer is preferable to the dial-barometers, although from time to time it is necessary to modify the graduation or to apply corrections on account of the variations to which the molecular state of the tube in the Bourdon barometer, or that of the metallic box and of the antagonistic spring in Vidi's instrument, is subject.

CHAPTER IX.

WEIGHT OF THE AIR AND OF GASES (*continued*).—PUMPS—MARIOTTE'S LAW—THE AIR-PUMP.

Principle of the ascent of liquids in pumps—Suction and force pumps—The siphon—Air-pump; principle of its construction—Double and single barrel air-pumps—Condensing pumps--Mariotte's law.

THE discoveries of the weight of the air and of atmospheric pressure only took place a little more than two centuries ago. But long before Torricelli and Galileo, the application of the principle had taken precedence of the theory, as is proved in the account we have given, which history has handed down to us. It is, in fact, the pressure of the air which is the cause of the ascending movement of water in pumps. Now, the invention of these useful instruments is generally attributed to Ctesibus, a celebrated geometer and mechanician, who lived at Alexandria 130 B.C., or about a century after Archimedes.

We shall now describe briefly the different instruments known under the name of pumps, the object of which is the movement of liquids and gases, keeping here particularly in view the explanation of the action of these instruments: we shall return, in the volume which will treat of the applications of physics, to the detailed description of those which have a special use in the industrial arts.

Let us take a hollow cylinder, in which a piston furnished with a rod may be moved up and down, and in the bottom of which an orifice is made (Fig. 74). The piston having been lowered to the bottom of the cylinder, the instrument is immersed in a vessel or reservoir full of water; then the piston is raised by its rod. What happens? The space void of air, which the piston leaves under it in its ascending movement, will be filled with water, first until the level of the water is the same in the cylinder as in the reservoir: this takes place in virtue of the principle of the equilibrium of liquids in communicating vessels, so that this would happen even if there was air under the piston. But the water still rises above this level, keeping in contact with the piston, the lower surface of which it constantly touches; and it is easy to understand that its movement is due to the pressure which the outer air exerts on the liquid surface of the reservoir.

Let us suppose that the cylinder has an elevation of more than 32 feet: the liquid column will rise until it attains about this height. At this moment its weight is in equilibrium with the pressure of the atmosphere; if the piston continues to rise, the water will not follow it. This is precisely the obstacle which the Florentine workmen encountered, and which caused the physicists belonging to the Court of the Grand Duke to believe that Nature ceased to abhor a vacuum beyond 32 feet.

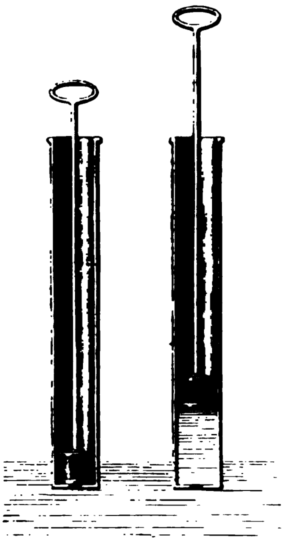

FIG. 74.—Principle of the suction-pump.

Such is the principle of the pump to which is given the name of suction-pump, because the piston appears to suck up the liquid as it rises. We will now show how the instrument is generally arranged when it fulfils the object for which it is intended; that is, to give us a supply of water which has been raised to a certain height above the level of the reservoir.

The cylinder, or the body of the pump, is furnished with a cylindrical tube of small diameter, the lower extremity of which is placed in the reservoir. At the junction of the cylinder and tube a valve is fitted, which opens upwards. The piston has itself one or more openings, furnished with valves, whose action is in the contrary direction to the first (Fig. 75). It will now be seen what will happen when we give an alternate movement to the piston in the body of the pump. At its first ascent a vacuum is made under it. The air in the suction-tube lifts the valve by its pressure, and the water rises to a certain height. When the piston again descends, the air which is introduced into the body of the pump is compressed: on the one hand, its pressure closes the lower valve, and, on the other, it lifts the valves of the piston and it escapes upwards. At each movement the water rises higher and higher, and at last comes in contact with the lower wall of the piston, and passes through the valves to its upper surface. It will be easily seen how the water is forced to flow out by a lateral orifice at the upper part of the pump. Moreover, once the pump is in action, when the piston rises, a vacuum is made beneath it, and the water continues to press against its lower side. The valve of the suction-tube remains constantly open, and the ascent of the water is determined by the movement of the piston.

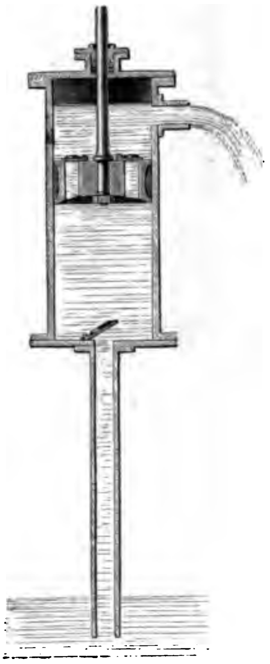
FIG. 75.—Suction-pump.

The effort necessary to raise and lower the piston, when the pump is in action, is easily measured. If the piston descends, its own valves are open; the pressures transmitted to its opposite sides by the liquid are equal the one to the other, and consequently are counterbalanced, and the only resistances felt proceed from the friction of the liquid and the piston. But if the piston is raised, the atmospheric pressure is alone annulled, as it is exerted on the reservoir on the one hand, and on the upper level of the liquid on the other, and the effort required is measured by the weight of a column of water, having for its base the surface of the piston, and for its height the vertical distance between the two levels of the liquid. If, for example, this distance is 2 metres, and the base of the piston is 1 square decimetre, it will require a force of 20 kilogrammes to raise the piston, without taking into account the resistances due to friction.

Experiment shows that it is not possible to give to the suction-pump a depth of more than about 20 feet, instead of 32 feet as indicated by theory. The reason of this lies in the escape of air and water which always takes place between the pump itself and the piston; besides, the water of the reservoir nearly always contains air in solution, and this frees itself from the liquid, because it is brought up to a region of less pressure.

In the force-pump (Fig. 76) the body of the pump is immersed in water, so that the liquid is introduced into it by simple communication. Moreover, the piston is solid, and the tube used to raise the water, starting from the lower part of the pump, is furnished at the point of junction with a valve which opens towards the outside. The piston in its descending course presses the water, this pressure shuts the valve of the pump and opens that of the conducting pipe, and forces the liquid out.

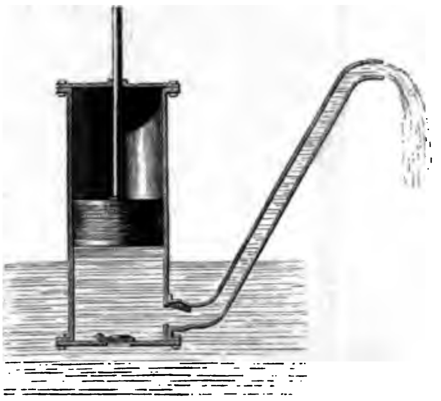

FIG. 76.—Force-pump.

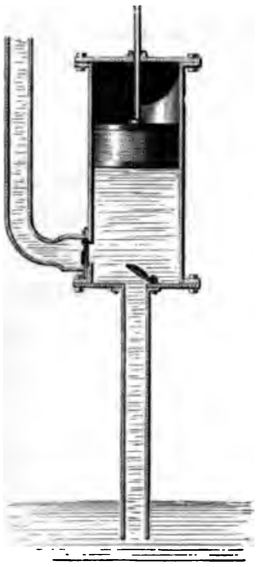

FIG. 77.—Combined suction and force pump.

The suction and force pump (Fig. 77) combines the arrangements of both the pumps we have just described. The ascent of the water is caused by suction; and since the piston is solid (*i.e.* is not furnished with valves), in coming down it presses the liquid into the lateral tube.

We will now describe an instrument known to most people—the siphon—which is of great use in transferring liquids from one vessel to another: it is the pressure of the air which causes the action in this case also. A tube formed of two curved branches, of unequal length, is filled with part of the liquid which is to be transferred, and its shortest branch is immersed in the vessel which contains this liquid (Fig. 78). As soon as this is done, the liquid is seen to flow from the opening at the end of the longest branch, as long as the shortest remains immersed.

What is the cause of this continual flowing? Nothing is more easy to explain. At the surface of the liquid in the vessel, and at the lower and free extremity of the tube, the atmospheric pressure is exerted with almost equal intensity and in contrary directions. At the point where the tube is in the vessel, this pressure serves to raise the liquid in the smallest branch, and would maintain it there in equilibrium, if the length of the two branches were the same and both the ends were immersed in it. Hence it follows that all the portion of the liquid contained in the tube and exceeding the level of the

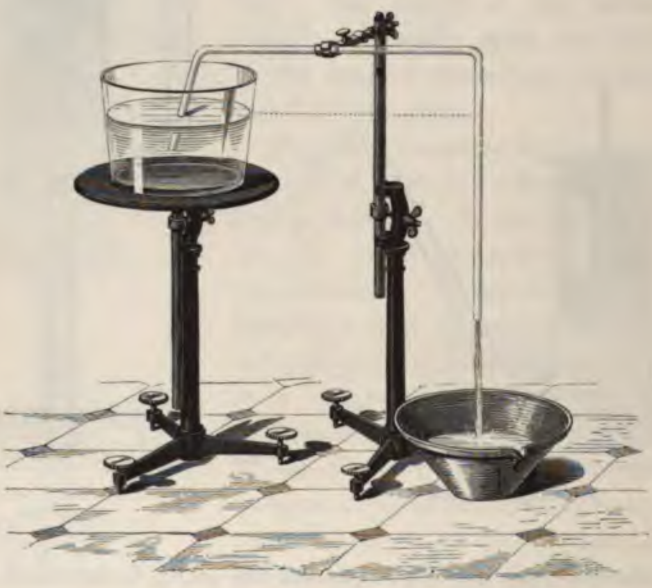

FIG. 78.—The siphon.

vessel, remains in equilibrium under the influence of these opposite pressures. There remains then in the large branch of the siphon a column of water whose gravity disturbs the equilibrium and determines the direction of flow.

It might be imagined that when once the liquid in the tube had escaped, the action would stop; but it must be remarked that to do this the two branches of the liquid must be separated by a vacuum, which the pressure exerted on the liquid in the vessel by the atmosphere tends continually to fill, so that in reality this separation does not take place, and the flowing continues.

The forms of siphons differ, according to the use to which they are destined, and also according to the nature of the liquid to be transferred. We shall describe some of them in another volume, when we explain their applications in great hydraulic works.

It only remains now for us to terminate the study of the phenomena of gravity, by describing the instruments which are used to exhaust the air from a receiver, or any vessel, or, on the other hand, to compress it there; then by stating how the pressures of gases are determined, and according to what laws these pressures vary when the volume which they occupy is made to vary.

Torricelli's experiment on the tube gave a very simple means of making a vacuum, and a vacuum as perfect as possible; for the space situated above the column of mercury, which has received the name of the barometric chamber, is a perfect vacuum. But if the process is simple, it is far from being practical, since it would necessitate the use of an enormous quantity of mercury, if the space which we wished to rarefy were considerable, and moreover the precautions required to be taken at each operation would be irksome. Thus long ago other means were sought. It was in 1654 that the first air-pump was thought of and constructed. Otto de Guericke was the inventor, and we have quoted many curious experiments due to this able physicist. It soon received important improvements from Boyle, Papin, Muschenbroek, and Gravesande. At first it was only formed of one cylinder; but the necessity of having two, to get rid of the great resistance which is felt while using it, was soon rendered obvious. As it is not in our programme to give the history in detail of the progress of any mechanical instruments, we will describe the air-pump as it is now used by all physicists.

And first let us deal with the principal arrangements. Let us imagine two cylinders, each furnished at the bottom with a valve which opens upwards, and with a piston having an orifice closed by a valve which opens in the same direction. The two orifices in the base of the cylinder communicate by a common pipe with a well-ground glass plate, on which the receiver is placed, and at the centre of which is the opening of the pipe. Fig. 79 shows in section one of the cylinders, its two valves, and the communicating canal. The action of this half of the instrument being well understood, it will be easy to comprehend the whole.

Let us begin at the moment when the piston touches the lower part of the cylinder. The receiver is filled with air at the atmospheric pressure. At the moment when we raise the piston, a vacuum is made in the lower part of the cylinder. The air of the receiver which filled the communicating canal lifts up the lower valve by its elastic force and spreads itself in the vacuum, the valve of the piston being kept shut by the pressure of the air which is exerted externally on all the surface of the piston. This passage of air from the receiver into the cylinder takes place until the piston has reached its highest position. It is clear that at this moment the quantity of air contained in the receiver has diminished, and that it has diminished one-half, if the volume of the cylinder is precisely equal to the volume of the receiver.

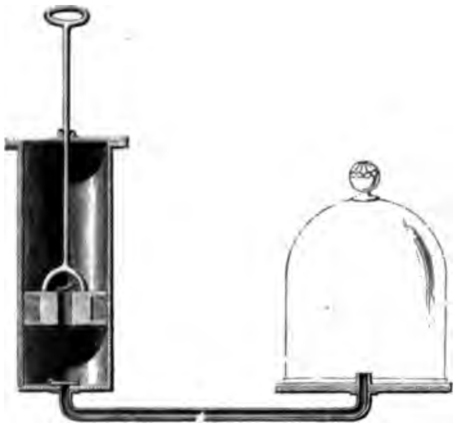

FIG. 79.—Action of the piston and valves in the air-pump.

Let us now send the piston in a contrary direction. At the moment when it begins to descend, the capacity of the cylinder diminishes, the pressure of the air which it contains increases, exceeds that of the air of the receiver, and the lower valve is closed. Then, in proportion as the descent of the piston lessens the capacity, the confined air increases in density: on our assumption of its capacity, this density will again become equal to that of the atmospheric air, as soon as the piston attains half of its course. Beyond this point the interior pressure increases, lifts up the valve of the piston, and the air escapes altogether, until the piston again rests on the lower part of the cylinder.

This single up-and-down movement, analysed in its effects, explains the whole of the operation, as it has sufficed to rarefy the air in the bell-jar one-half: that which remains will be again rarefied at a second, then at a third trial, and so on. The pressure will become the quarter, eighth, and then the sixteenth of the first pressure, as we shall soon see in explaining Mariotte's law. This proportion would of course change, if the ratio of the capacity of the cylinder to that of the receiver were changed.

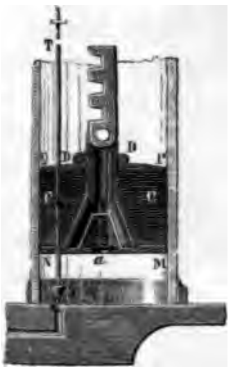

FIG. 80.—Detail of the piston and its valves.

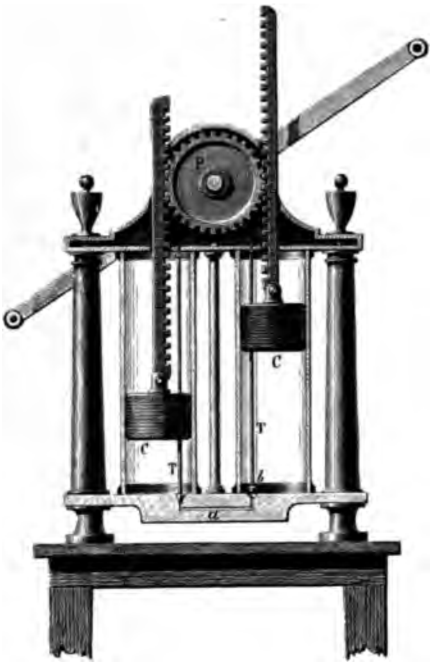

FIG. 81.—Air-pump with two cylinders. Transverse section.

Figs. 80, 81, 82, and 83 will now explain the real arrangement of the air-pump, and show the utility of the second cylinder. The first shows how the two valves are placed, that in the piston and that at the bottom of the cylinder. The valve of the piston is a small plate *a*, with a light spring pressure on the opening, but which gives way to a very slight pressure in the contrary direction. The valve of the cylinder, *b*, is conical; a rod, T, which moves by friction in the piston, raises or lowers it, but only for a very short distance. Fig. 81 shows that the rods of the pistons are formed with rackwork which works into a pinion, so that, with the help of a handle with two arms, it is possible to lower one piston and raise the other. Thanks to this arrangement, the work done is doubled; but—and this is the end for which it was proposed—the resistance is reduced to its minimum; for, in proportion as the vacuum is made, each piston when rising must overcome the atmospheric pressure which acts on its base; but, on the other hand, this pressure helps the other piston to descend. In this way, then, there is a compensation or equilibrium between these two forces which act, it is true, in the same direction, but all the force is done away with by the resistance of the pump, without fatiguing the operator. Figs. 82 and 83 give the plan and the exterior view of the air-pump with two cylinders.

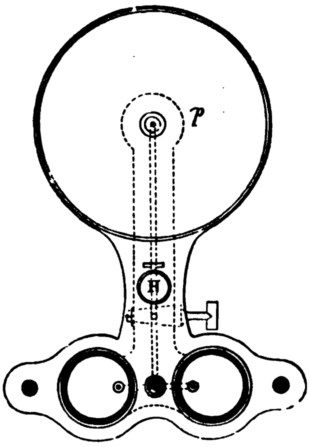

FIG. 82.—Plan of the air-pump with two cylinders.

It will be seen how the pipe, which unites the two cylinders by a tube, communicates at the centre with the plate, which is of ground glass, perfectly plane, on which is fixed the well-greased edge of the receiver in which the vacuum is to be made. If the receivers have the form of tubes or balls, &c., they are screwed into the aperture in the centre of the plate.

A stopcock in the middle of the tube of communication is pierced with holes, which enable us either to establish or close the communication between the pump and the receiver, or to permit the exterior air to penetrate into the cylinders or into the receiver only.

In the same pipe, a bell glass (H, Fig. 83) is seen, containing a barometric tube, or manometer, which is used to indicate to what degree the exhaustion has proceeded in the receiver; that is to say, what is the pressure of the quantity of air which this latter still contains.

Lastly, the best air-pumps are furnished with an arrangement, the invention of which is due to M. Babinet. This is a stopcock by the aid of which, and a special pipe, the receiver is allowed to communicate with one cylinder only. The air which it still contains is forced through another pipe under the piston of the second cylinder, and there, thanks to the increase of pressure which follows, it ends by raising the valve. The degree of vacuum is thus extended to a limit, such that the pressure of the air which still remains in the receiver is scarcely appreciated by the manometer.

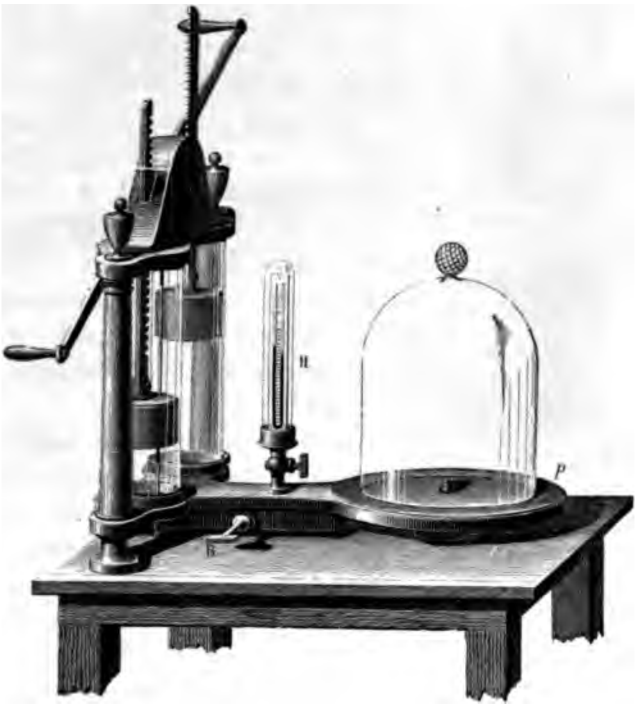

FIG. 83.—Exterior view of the air-pump.

Bianchi's air-pump has only one cylinder. But the piston divides it into two compartments, which alternately receive and expel the air: it is, properly speaking, a double-action pump. Fig. 84

explains the manner in which this pump acts. A rod supports the two moveable conical valves, which shut and open alternately under the action of the piston, thus opening and closing the communication of each compartment with the receiver. The air of the lower compartment, compressed when the piston descends, raises a valve held by a spring, over the orifice of the pipe formed in the piston-rod; it escapes to the outside by this pipe. The air of the upper compartment escapes by a valve of the same kind fitted to the lid of the cylinder. A system of toothed wheels is put into motion by a handle; and as the cylinder can oscillate in a vertical plane, the alternate movement of the piston is accomplished by a continuous movement of rotation, the velocity of which is regulated by a very heavy fly-wheel (Fig. 85). With this machine a vacuum can be rapidly produced in receivers, the capacity of which may increase with the dimensions of the cylinder.[1]

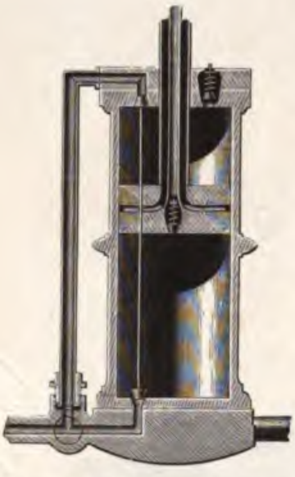

FIG. 84.—Bianchi's air-pump; interior view of the cylinder.

We have had already several times occasion to describe some curious experiments made by the aid of the air-pump: we shall in the sequel refer to others, connected with the phenomena of heat, sound, and electricity. We shall content ourselves here by indicating some which concern the phenomena of weight. For example, it is proved that water ordinarily contains, in solution, air retained in it by the atmospheric pressure. In the receiver, we see the bubbles of air attached to the sides increase as the pressure diminishes, and mount to the surface of the water. Smoke, which in the atmosphere rises above the lower strata, falls *in vacuo* like a heavy

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[1] M. Deleuil has constructed an air-pump specially intended for industrial uses, the piston of which does not touch the walls of the cylinder. The thin stratum of air which remains in the space serves as a fitting to the piston, so that the resistance due to the friction of the piston in the ordinary cylinder is done away with. M. Deleuil obtains in a receiver of 14 litres in capacity a degree of rarefaction measured by 3 millimetres of pressure only.

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mass. This phenomenon shows that the principle of Archimedes is true for gases as for liquids, as may be shown by another experiment with a little instrument called a baroscope, the inventor being Otto de Guericke. A balance supports at each end of its beam two metallic balls, the one hollow and thin, the other solid and of small volume: weighed in air, these two balls exactly establish equilibrium (Fig. 86). When the apparatus is brought beneath the receiver of the air-pump, we see the equilibrium disturbed when the air is exhausted, and the beam is inclined towards the largest sphere. This sphere lost then in the air a certain portion of its weight, which is precisely equal to the weight of the displaced air. This proves to us that to determine the exact weight of bodies, it is necessary to weigh them *in vacuo*, or at least to correct the error due to the pressure of the air. For delicate weighing in chemistry, or for the precise determination of densities, this correction is indispensable.

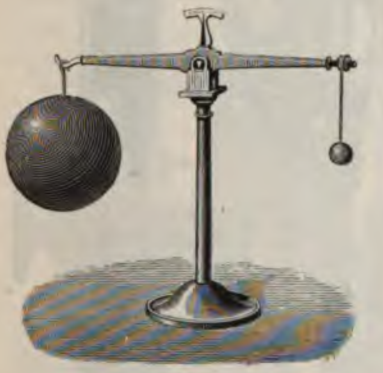

FIG. 86.—The baroscope.

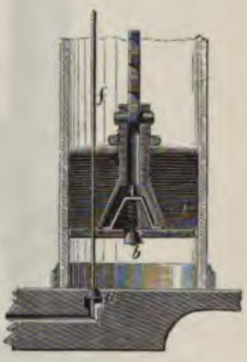

FIG. 87.—Condensing machine. Interior view of the piston.

The application of the principle of Archimedes to balloons or aërostats will form the subject of a future description[1]

Instead of making a vacuum in a vessel or receiver, it is possible, on the contrary, to accumulate and to compress the air or other gases within it. This operation is accomplished by means of condensing machines or pumps.

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[1] Applications of Physics.

Condensing machines are constructed exactly like air-pumps, with one modification—all the valves open in a contrary direction. On examining Fig. 87, which represents a section of the condensing machine, it will be immediately seen what is the action of the mechanism, and how, instead of rarefying or expelling the air, the oscillatory movement of the piston must on the contrary accumulate and compress it.[1]

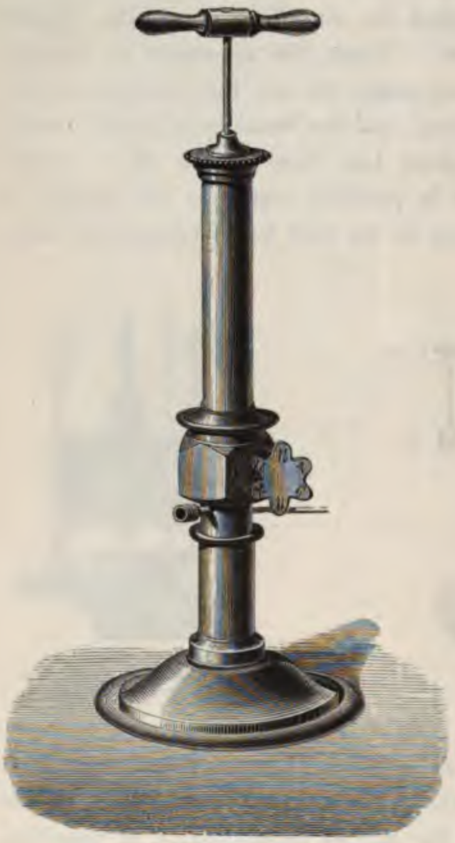

Fig. 88.—Silbermann's condensing pump. Exterior view.

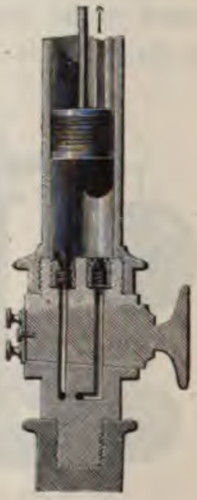

Fig. 89.—Silbermann's condensing pump. Section.

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[1] The condensing pump of this kind, of which we here give the section and the exterior view, is due to a physicist whose merit equals his modesty, M. J. Silbermann, *préparateur* of the Course of Physics to the College of France. If we had more space, we should explain how the stopcock, the position of which is shown

At the present day, condensing pumps formed with one cylinder, a solid piston, and the two valves of which are placed at the bottom of the cylinder, one communicating with the outer air, the other with the receiver (Figs. 88 and 89), are used in preference. If a more rapid compression is required, a pair of pumps is used. Fig. 90 shows the general arrangement of instruments of this kind. M. Regnault

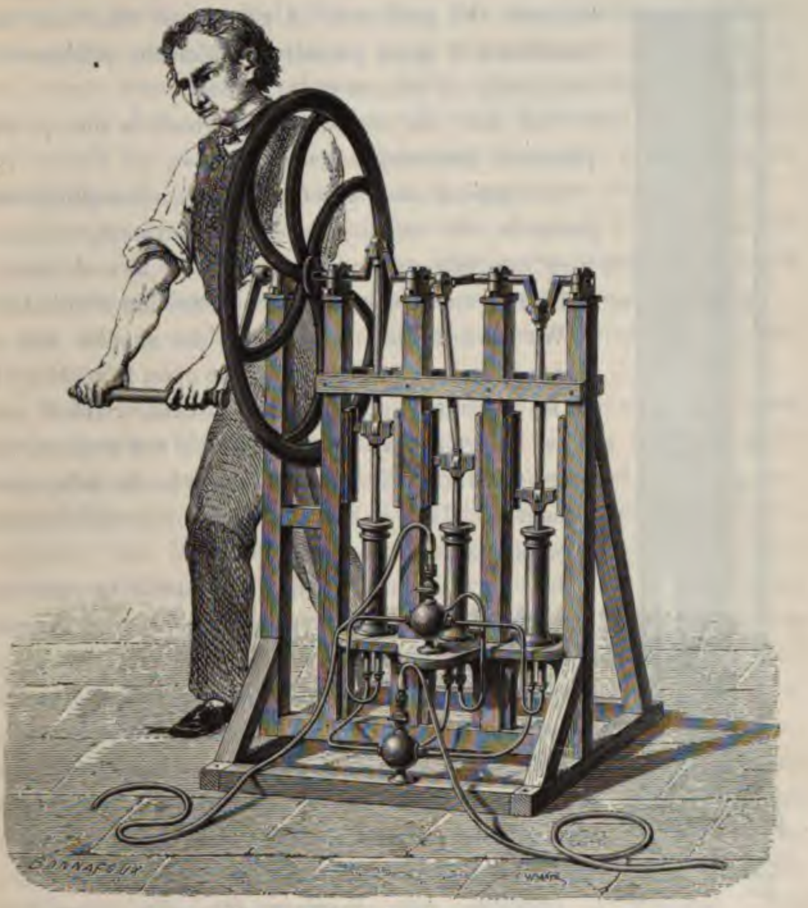

FIG. 90.—Connected condensing pumps.

below the valves, enables us to condense in a receiver, air or any other gas contained in the other; to reverse the order of communication of the receivers; or, again, to re-establish between them equilibrium of pressure; lastly, to make a communication between them and the atmosphere. It is both an air-pump and a condensing pump.

used it to obtain air or vapour, the pressure of which was equivalent to thirty times the atmospheric pressure, or capable of supporting a column of mercury thirty times 76 centimetres; that is, 22·80 metres.

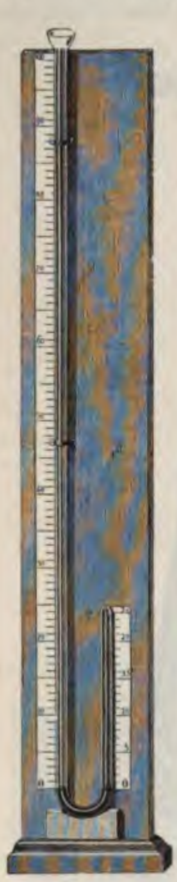

FIG. 91.—Experimental proof of Mariotte's law.

Let us now state on what principle we rely to estimate the pressures of gases, and what law the variations of these pressures, under the influence of the change of volume only, follow.

This law, the discovery of which is due to the physicist Mariotte, is given thus:—

If a gaseous mass is submitted to a series of different pressures, the volumes which it successively occupies vary inversely as the pressures which it undergoes.

Here is an experimental demonstration of this law:

We take a long bent tube, the smaller arm of which is closed, and the large one open (Fig. 91). If it is perfectly cylindrical, the scale, divided into equal parts, the divisions of which are seen on the stand to which it is fixed, indicates in the tube equal capacities. If it is not cylindrical, it is divided into unequal portions of equal capacity.

Let us introduce a certain quantity of mercury, and, by shaking, make the liquid extend in two columns of the same height, the levels of which correspond to the zeros of the two scales. At this moment, equilibrium exists between the outer air which presses the mercury in the large open arm, and the interior air confined in the closed arm. The pressure of the latter is then equal to that of the atmosphere.

Let us pour mercury into the large arm. Equilibrium will be disturbed, and the mercury will rise in the closed arm. Let us stop when the level will attain division 12; that is to say, when the volume of gas will be reduced one-half. We shall prove that the difference of the levels of the mercury will be precisely equal to the barometric height at the moment of the experiment. Now, it is clear that at this moment it is this difference of level which measures the increase of pressure of the confined gas; the total pressure is then two atmospheres.

On again pouring mercury into the large arm, we shall see the level rise in the smaller branch as far as the divisions 16, 18, 19.2 for example, which supposes the volume of gas reduced to a third, quarter, and fifth of its original volume. Now, it is found that the pressures are successively three, four, five atmospheres. Generally, the volume occupied by the air or by any other gas varies precisely in inverse ratio to the pressures which this gas supports; which proves the law. The law is proved with the same facility when we submit the gaseous mass to decreasing pressures: lower than the atmosphere the volume increases as the pressures diminish.

It is seen by this law, the importance of which is extreme, how gases are compressible, and how they differ in this respect from liquids the compressibility of which is confined within very narrow limits.

In the preceding experiments, the temperature is supposed constant.

If Mariotte's law were exactly true, it would follow that all gases are endowed with equal compressibility, and that it increases however great the pressures to which they are submitted. Dulong and Arago have proved the exactitude of the law, for air, to 27 atmospheres; but M. Despretz and M. Regnault (later) have arrived at the conclusion that this compressibility is not precisely the same for all gases, and, moreover, that it is slightly variable for the same gas. Air, nitrogen, and carbonic acid are really condensed more than Mariotte's law would allow; hydrogen acts in a contrary direction. As to the gases susceptible of passing into a liquid state, the variation has been found much more considerable, according as the experiments have been made at a temperature nearer that at which they are liquefied. Doubtless, at this temperature the gases undergo molecular modifications the nature of which is not yet known, but which differs from the effects due to the variations of pressure. The measure of the pressure of the air which remains under the receiver of the air-pump when a vacuum is made, a measure effected with the help of a manometer or short barometer, is a direct application of Mariotte's law.

BOOK II.

SOUND.

CHAPTER I.

THE PHENOMENA OF SOUND.

THE absence of all sound, of all noise, in a word absolute silence, is to us synonymous with immobility and death. We are so accustomed to hear, if it is only the noise we ourselves make, that we can scarcely conceive the idea of a world completely silent and dumb, as the moon appears to be, if we are to believe astronomers.

Phenomena of sound are perpetually manifested on the earth, although of course there is in this respect a great difference between our great cities, the thousand noises of which are perpetually deafening us, and the low and confused murmur which is heard in the solitude of the fields, on the mountains, or in the plains. We must note also the contrast there is between the calm of the Alpine and the Polar regions, in which all life disappears, and the resounding shores of the ocean! There the silence is only broken by the dull rolling of avalanches, the cracking of ice, or by the roaring of violent gusts of wind. The rumbling of thunder, so prolonged in the plains or in valleys, does not exist on the highest mountains: instead of the terrible report which generally characterizes thunderclaps, and the repercussion of which multiplies the duration, there it is a harsh sound, similar to the discharge of fire-arms. On the sea-shore, on the contrary, the ear is deafened by the continuous sound of the waves which unfurl or break on the rocks, and by the dull, uniform roaring, which like a solemn bass accompanies the sharper notes which the waves produce when they strike the sand and pebbles. In the midst of fields and forests the sensation is quite different. We hear a dull moaning formed by the union of a thousand varied sounds: the grass which bends under the wind, the insects which fly or creep about, the birds whose voices are lost in the air, the sound of the branches of the trees which rustle under the impulse of the light breeze, or which are bent and broken by violent winds. From all this comes a harmony, sometimes gay and sometimes grave, but always different from the discordant clatter which fills the populous streets of great towns.

Watercourses, rivers, brooks, and torrents join their notes to this concert; in mountainous countries there is the noise of cascades which dash upon the rocks, and sometimes the terrible roaring of falling rocks which destroy and bury all in their passage.

But of all natural sounds, the most continuous and violent are those which arise and are propagated through the atmosphere: masses of air dragged along by an irresistible movement, sometimes shrieking, sometimes roaring with fury, strike against all obstacles which oppose them, such as the unevenness of the ground, mountains, rocks, forests, or solitary trees. When electricity is associated with these actions they become more terrible, and the frightful reports of thunder drown all other sounds. Volcanic explosions and earthquakes alone rival in power this great voice of nature. An immense detonation was heard under the towns of Quito and Ibarra, arising from the catastrophe which destroyed Riobamba in February 1797; but, curiously, it was not heard at the place of the disaster. The upheaval of Jorullo, in 1759, according to Humboldt, was preceded by subterranean roarings which lasted two entire months.

To complete this list of sounds naturally produced in the earth and the atmosphere, there remains for us to mention the detonations which accompany the fall of cosmical meteors, aërolihs, and bolides. These explosions usually occur at great heights, and persons who have heard them compare them either to the discharge of artillery or to the prolonged rolling of thunder.

The phenomena of sound which are most interesting to us are those which men and animals produce by the aid of special organs: the human voice, that indispensable interpreter of our thoughts and sentiments; and the cries of animals, which express in a ruder manner the various impressions which they feel, their wants, joys, and griefs. The most powerful of all arts—music—was created by man to express that which articulated language could not express; and to add still more to the gifts of nature, he has discovered how to multiply the resources of his voice by the aid of various instruments.

The necessities of labour and of human industry have caused man to produce many other sounds and noises which do not commend themselves either for melody or harmony, but most of which are inseparable from the works which have engendered them, and share, so to speak, in their character of utility. In manufactories and workshops, and in forges, the noise of hammers and saws, of all sorts of tools, and of steam-engines, often continues uninterruptedly night and day. But how can it be helped? To our mind, it is a music which is infinitely preferable to that of musketry and cannon on the field of battle; as is the contest of work and of science against the actions of brute force.

However varied the several phenomena we have passed in review may appear, they in reality all relate to one mode of movement, of which we must study the nature and formulate the laws. We will commence by enumerating the different ways in which sound can be produced and propagated, in solids, liquids, and gases.

CHAPTER II.

PRODUCTION AND PROPAGATION OF SOUND.—REFLECTION OF SOUND.—VELOCITY OF SOUND IN DIFFERENT MEDIA.

Production of sound by a blow or percussion, and by friction, in solids, liquids, and gases—Production of sound by the contact of two bodies at different temperatures; Trevelyan's instrument—Chemical harmonicon—The air a vehicle of sound; transmission of sound by other gases, by solids and liquids—Propagation of sound at great distances through the intervention of the ground—Velocity of sound through air; influence of temperature; experiments of Villejuif and Montlhéry—Velocity of sound in water; experiments made on the Lake of Geneva, by Colladon and Sturm—Velocity of sound through different solid, liquid, and gaseous bodies.

PERCUSSION, or the shock of two bodies against each other, is one of the most usual methods by which sound is produced. The hammer which strikes the anvil, the clapper which causes bells to sound, drumsticks, the rattle, and a hundred other instances which the reader will easily call to mind, are examples of the production of sound by the percussion of solid bodies. The most varied noises can thus be obtained, but we shall find that this variety depends both on the form and the nature of the sonorous body and on the way in which the sound is conveyed to our ears. In the water-hammer experiment, the noise proceeds from the shock of a liquid mass against a solid body.

Friction is another cause of the production of sound or noise: thus it is that by the aid of a bow, the horsehairs of which have been rubbed with a resinous substance called colophane, the extended cords of certain stringed instruments are made to resound; so also in the case of bells of glass or metal. But sounds are also obtained by longitudinal friction applied to cords or metallic rods. When certain substances, such as wood, stone, &c. are drawn along the ground, they produce a noise which is due to friction: carriage-wheels which roll along the roadway also produce a sound which in great part is due to friction, but also to some extent to percussion. The act of drawing aside a tense cord, as is usual in playing instruments like the guitar, harp, or mandoline, produces a sound which is due both to percussion and to friction.

When liquid and solid bodies are brought into contact by means of percussion or friction, sounds and noises are produced; but the same movements in liquids, without the intervention of solid bodies, also produce sound: such is the agitation which is produced by the fall of raindrops on the surface of a pond or river.

In gases, sound, as we shall presently see, is caused by a series of condensations alternating with dilatations; but it may also be induced by percussion or friction. Thus, the air hisses when it receives a violent stroke from a cane or whip: and the wind produces loud sounds when it strikes against trees, or houses, or other solid bodies. The roaring sound which is sometimes heard in chimneys is due to a movement of the air which we shall study when we consider the nature of the sounds produced by the movement of gases in tubes. Of the same kind is the sound produced by those musical instruments which are known as wind instruments. The human voice and the cries of animals belong also to this class.

Explosions of gases, the noise which accompanies the electric spark and the reports of gunpowder, are sounds caused by rapid changes of volume, and by successive dilatations and contractions of gaseous masses. Among the most remarkable modes of producing sound, we may mention the contact of two solid bodies at different temperatures. This singular phenomenon was described for the first time in 1805, by Schwartz, the inspector of a Saxon foundry. Having placed a silver ingot at a high temperature on a cold anvil, he was astonished to hear musical sounds during the cooling of the mass. In 1829, Arthur Trevelyan accidentally placed a warm soldering iron on a block of lead; almost immediately a sharp sound was heard. He was thus induced to study the phenomenon under different conditions, and he invented various instruments to illustrate the cause of the production of this sound: these will be described when we speak of sonorous vibrations.

The passage of an electric current produces sound in a bar of iron suspended at its centre, and one extremity of which is in the centre of an induction coil.

Lastly, the combustion of gases in tubes gives rise to the production of musical sounds. If we light a jet of hydrogen generated by the small apparatus called by chemists the philosophical lamp, and introduce it into the interior of a tube of greater diameter than itself and open at both ends, we hear a sharp or dull sound, which varies with the length, diameter, thickness, and nature of the substance of the tube. If several of these tubes are arranged together, a series of musical sounds may be obtained, and tunes may be produced; hence the name of "chemical harmonicon" by which this musical instrument is known. This fact was the starting-point of the curious experiments of Schaffgotsch and Tyndall on singing flames.

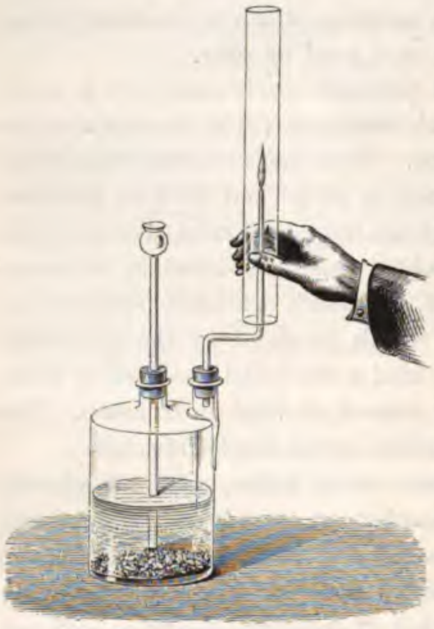

FIG. 92.—Philosophical lamp or chemical harmonicon.

Hitherto we have considered the production of sound or noise in sonorous bodies which may be either solid, liquid, or gaseous; let us now inquire how sound, that of a clock which is striking, for instance, reaches our ears. We can answer this question by means of observations and very simple experiments, even before we understand the real nature of the phenomenon of sound.

It is a well-known fact that sound takes an appreciable time to travel from a sonorous body to the ear. When we see a person at some distance from us who is striking blows with a hammer, we see the hammer fall before we hear the noise of the percussion. In the same way the report of a gun or cannon reaches the ear after the flash produced by the explosion has been visible to the eye. In all these cases, the interval included between seeing the flash and hearing the sound, indicates a difference between the velocity of light and that of sound; but as the velocity of light, compared with that of sound, may be considered as infinite, this interval gives without any perceptible error the time which sound takes to be propagated from one point to another. We also learn by daily observation that this interval increases with the distance. I remember having admired on the coast of the Mediterranean the curious spectacle of a man-of-war practising with cannon. I saw the smoke of the guns, then the ricochet of the cannon-balls on the crests of the waves, long before I heard the thunder of the report.

Sound is propagated by a succession of impulses; we shall soon learn with what velocity. But what is the medium which serves as a vehicle to this movement? Is it the ground? Is it communicated by the intervention of solids, liquids, or the air, or by these several media at once? The following experiment will answer these questions.

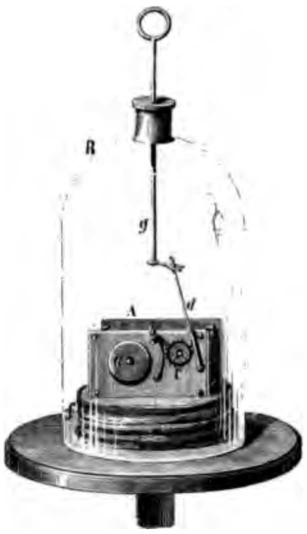

FIG. 93.—Sound is not propagated in a vacuum.

Let us place under the receiver of an air-pump a clockwork arrangement furnished with a bell, the hammer of which is temporarily fixed, but is capable of being moved at will by a rod (Fig. 93). Before exhausting the receiver, the bell is distinctly heard when struck by the hammer. But in proportion as the air is rarefied the sound diminishes in intensity; and as soon as the vacuum is approximately perfect, it is completely lost if the precaution has been taken to place the apparatus on a cushion of cork, or wadding, or any substance which is soft and more or less elastic. The hammer is then seen to strike the bell, but no sound can be heard. If we now introduce into the receiver any other gas, such as hydrogen, carbonic acid, oxygen, ether-vapour, &c., the sound is again heard. Thus air and all gases are vehicles of sound. But they do not all possess this property to the same extent. Thus, according to Tyndall's experiments, the conductivity of hydrogen gas for sound is much less than that of air, at an equal pressure, while the velocity of propagation is nearly four times greater in hydrogen than in air.

Solid bodies also transmit sound, but in very varied degrees depending on their elasticity. Thus in the preceding experiments, even when the vacuum is nearly perfect, if we place the ear close to the receiver, we hear a very feeble sound transmitted to the surrounding air by the cushion and the plate of the air-pump. The transmission of sound through solids is proved even better by the fact that the sound of the bell is simply enfeebled if we place the clockwork apparatus on the glass plate of the air-pump without the intervention of a soft cushion.

Water, and liquids in general, are also vehicles of sound, and as regards intensity and velocity are better conductors than air. A diver when under water hears the least noise; for example, that made by flints rolling and knocking against each other.

We must not confound the sounds which we perceive through the medium of the air with those which solids such as the ground or elastic bodies transmit to us. If the ear be placed at the extremity of a rather long piece of wood, we can clearly distinguish the noise produced by the friction of a pin or the tip of a feather at the opposite extremity, while a person standing near the middle, but with his ear not close to the wood, hears nothing. The ticking of a watch hung at the end of a long tube of metal is distinctly heard at the other end, while those near the watch do not perceive any sound. Hassenfratz, "having descended one of the quarries under Paris, instructed some one to strike the walls of one of the subterranean galleries with a hammer: he gradually went further away from the point where the blows were given, and on placing his ear against the wall he distinguished two sounds, one being transmitted by the stone and the other by the air. The first arrived at the ear much sooner than the other, but it also died away much more rapidly in proportion as the observer removed further from the source, so that it ceased to be heard at the distance of a hundred and thirty-four paces, while the sound transmitted by the air only ceased to be heard at a distance of four hundred paces." (Haüy.)

Similar experiments, when tried with long wooden or iron bars, give the same result, both as to the higher velocity and reduced intensity.

Humboldt, in describing the dull noises which nearly always accompany earthquakes, quotes a fact which shows the facility with which solid bodies transmit sound to great distances. "At Caracas," he says, "in the plains of Calabozo and on the borders of Rio-Apure, one of the affluents of the Orinoco, that is to say over an extent of 130,000 square kilometres, one hears a frightful report, without experiencing any shock, at the moment when a torrent of lava flows from the volcano Saint-Vincent, situated in the Antilles at a distance of 1,200 kilometres. This is, as regards distance, as if an eruption of Vesuvius was heard in the North of France. At the time of the great eruption of Cotopaxi in 1744, the subterranean reports were heard at Honda, on the borders of Magdalena: yet the distance between these two points is 810 kilometres, their difference of level is 5,500 metres, and they are separated by the colossal mountainous masses of Quito, Pasto, and Popayan, and by numberless ravines and valleys. The sound was evidently not transmitted by the air, but by the earth, and at a great depth. At the time of the earthquake of New Granada, in February 1835, the same phenomena were reproduced in Popayan, at Bogota, at Santa Maria, and in the Caracas, where the noise continued for seven hours without shocks; also at Haiti, in Jamaica, and on the borders of Nicaragua."

To resume: the transmission of sound from a sonorous body to the ear can be effected through the medium of solids, liquids, or gases, but the atmosphere is the most usual medium. Hence it follows that there is no sound beyond the limits of the atmosphere. The noise of volcanic explosions, for example, cannot reach the moon; and in like manner the inhabitants of the earth do not hear sounds which may be produced in interstellar spaces. The detonations of aërolites therefore prove that these bodies at the moment of explosion are within our atmosphere, the limits of which have not been precisely determined. On high mountains the rarefaction of the air produces a great diminution in the intensity of sounds. According to Saussure and others, a pistol fired at the top of Mont Blanc makes less noise than a small cracker. Ch. Martins, in describing a storm which he witnessed in these high regions, says, "The thunder did not roll; it sounded like the report of firearms." Gay-Lussac, during his celebrated balloon ascent, remarked that the sound of his voice was considerably weakened at a height of 20,000 feet.

Let us now inquire with what velocity sound is propagated through the different media we are about to describe; and first of the velocity of sound through air.

Many scientific men of the last centuries, among whom were Newton, Boyle, Mersenne, and Flamsteed, endeavoured to determine this velocity, either theoretically or by experiment, but the numbers at which they arrived were either too low or too high. We owe the first precise experiments to the commission of the Académie des Sciences in 1738. Again, in 1822, several physicists made determinations in the same manner, and the following was their method of proceeding. They were divided into two groups, which were placed respectively at Montlhéry and at Villejuif, these two stations being chosen because there was no obstacle to interfere with sight.

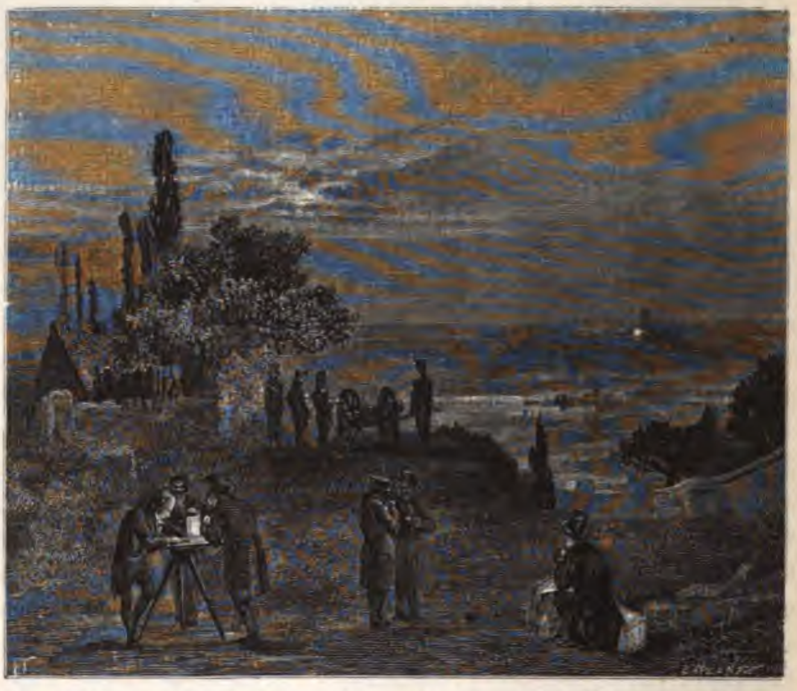

FIG. 94.—Measure of the velocity of sound through air, between Villejuif and Montlhéry, in 1822.

Gay-Lussac, Humboldt, and Bouvard were at Montlhéry; Prony, Arago, and Mathieu at Villejuif. They were each provided with a good chronometer; and two pieces of cannon of equal bore, charged with cartridges of the same weight, were placed at each of the stations.

The experiments began at eleven o'clock in the evening, with a serene sky and a nearly calm atmosphere. Twelve alternate shots at intervals of ten minutes were fired from each station, starting from a given signal, and each group of observers noted the number of seconds which elapsed between the appearance of the light and the arrival of the sound. The mean of the different numbers was 54 seconds 6 tenths; and as the distance of the two pieces of artillery, carefully measured, was 18,612 metres 5 decimetres, they concluded that sound travels 340 metres 9 decimetres a second (1118·152 feet) in air at a temperature of 16° C. The reciprocity of the determinations was in order to compensate for the influence of the wind. The temperature of the air exercises an influence which theory and experiment have equally confirmed. If the temperature increases, sound is propagated with much greater rapidity; and the velocity diminishes with the fall of temperature.[1]

But because the velocity of sound varies with the temperature, and also as we shall presently see with the humidity or hygrometric state of the air, the results obtained are probably more or less inexact. The strata of air in which sound is propagated are far from being homogeneous, and it is now known that their temperature during the night increases with the height. To avoid these different causes of error, M. le Roux measured in a direct manner the velocity of sound through a mass of air contained in a cylindrical tube of 72 metres in length. The air was dried, and its temperature kept at 0° by surrounding the tube with ice. The sonorous impulse was produced by the single blow of a wooden hammer, which was caused to strike a membrane of caoutchouc stretched over one of the extremities of the tube. This impulse, after having travelled along the tube, set in motion a second membrane stretched at the other extremity of the tube. Lastly, the beginning and the end of the propagation were registered automatically by electricity, and its duration measured by a particular kind of chronoscope. Numerous experiments gave M. le Roux a velocity of 330·66 m. a second: a number almost identical with the velocity, at the same temperature, 0°, indicated by the experiments of the Bureau des Longitudes in 1822.

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[1] In addition to the preceding experiments, we must quote those of Benzenberg in 1811; Goldingham in 1821; Moll and Van Beeck, Stämpfer and Myrbach in 1822; lastly, of Bravais and Martins in 1844. If we reduce the various determined velocities to zero, and calculate them as having been made in dry air, we obtain as a result a mean of 332 metres, or 1088·96 feet a second.

If we adopt this last number, we deduce for the velocity of sound at different temperatures, from —15° C. to 50° C., the following numbers:—

VELOCITY OF SOUND IN AIR.

Temperature (C.)	Number of metres per second.	Number of yards per second.
— 15°	321·46	350·92
— 10°	326·23	356·10
— 5°	327·62	357·60
0°	330·66	360·90
+ 5°	333·67	364·18
+ 10°	333·66	364·17
+ 15°	339·62	370·73
+ 20°	342·55	373·89
+ 25°	345·46	377·05
+ 30°	348·34	380·22
+ 35°	351·20	383·39
+ 40°	354·04	386·40
+ 45°	356·85	389·50
+ 50°	359·65	392·56

The experiments of 1738 and 1822 not only resulted in the determination of the velocity of sound; they also proved that this velocity is not modified by variations of atmospheric pressure: that the wind increases or diminishes it according as it blows in the same or in a contrary direction, whilst it does not effect any change if it blows in a direction perpendicular to that of the transmission of the sound.

Furthermore, this velocity is uniform at every portion of the distance traversed, and it is the same with sharp or dull sounds, feeble sounds, or those whose intensity is considerable. We are all aware that neither the time nor the precision of a piece of music executed by an orchestra is altered, whatever may be its distance from the listener. When the distance increases, all the sounds are lessened in the same degree, but this is the only alteration which they suffer, which could not happen if tones or sounds of different intensity were propagated with different velocities. Lastly, the velocity of sound through air appears to be the same in a horizontal, vertical, or oblique direction. This fact results from the observations made in 1844 by Martins and Bravais, between the summit and the base of the Faulhorn, and by Stämpfer and Myrbach at two stations situated at different heights above the level of the sea.

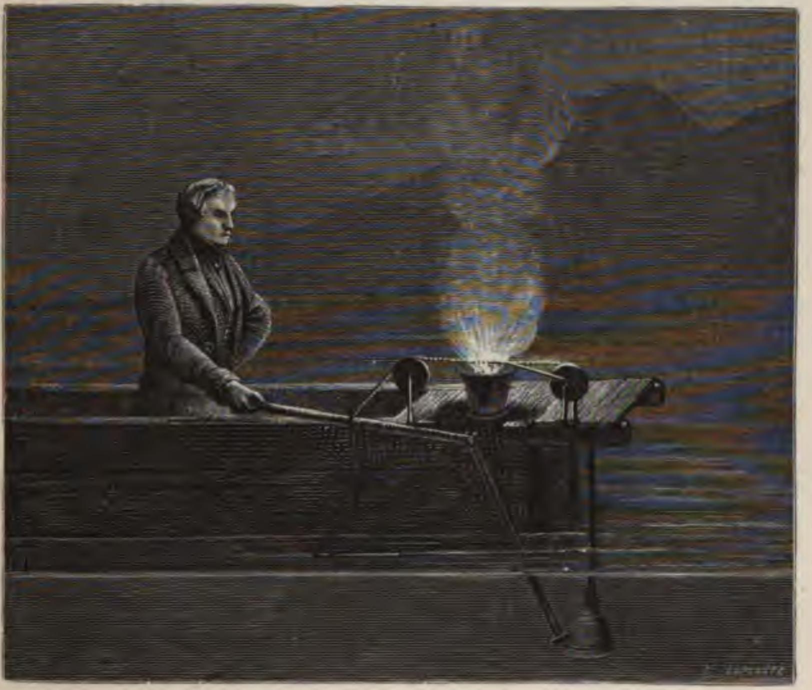

FIG. 95.—Experimental determination of the velocity of sound through water.

Very singular consequences follow from the difference which exists between the velocities of light, sound, and projectiles. Thus the soldier struck by a cannon-ball can see the fire which comes from the mouth of the cannon, but he does not hear the noise because the velocity of sound is less than that of the bullet; but if he is struck at a great distance, as the resistance of the air diminishes more and more the velocity of the projectile, it may happen that he sees the light and hears the shot before he is struck.

Sound is propagated through water with about four-and-a-quarter times the velocity through air. This was shown by some experiments made on the Lake of Geneva by two *savants,* Colladon and Sturm. Their mode of experimentation was as follows. The observers were seated in boats, one moored at Thonon, the other on the opposite shore of the lake. The sound was produced by the stroke of a hammer on a bell immersed in the water, and at the other station, a speaking-trumpet, having a mouth of large aperture, also under the water, received the sound propagated by the liquid mass by means of a sheet of metal placed over the opening. The observer, whose ear was placed at the mouth of the trumpet, was furnished with a chronometer or chronograph, which indicated seconds and fractions of a second; and he was made aware of the precise instant when the bell was struck by the flash produced by the ignition of some powder, which was ignited by the lowering of a lighted match fastened to the hammer in the

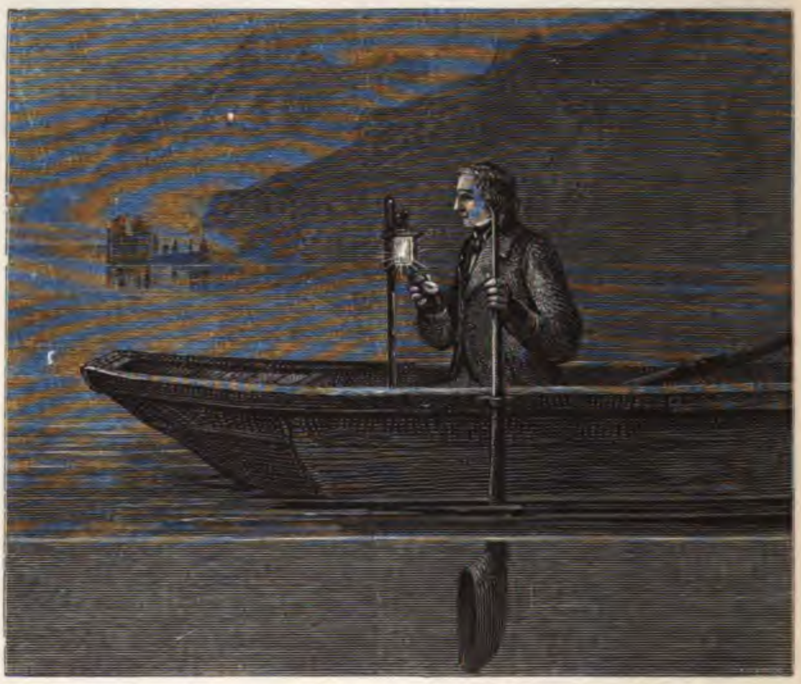

FIG. 96 - Experiments made on the Lake of Geneva, by Colladon and Sturm.

form of a lever. Figs. 95 and 96 indicate the arrangement, and will remove the necessity for a more detailed explanation.

The distance of the stations—13,487 metres—was traversed by the sound in nine seconds and a quarter, which gives 1,435 metres for the velocity of sound in water at a temperature of 8° C.

Lastly, the velocity of sound in solid bodies has also been experimentally determined. M. Biot, having operated on a cast-iron pipe 951 metres in length, found that sound is propagated through this metal with a mean velocity of 3,250 metres a second, which is more than nine-and-a-half times the velocity through air at the same temperature.

The velocities of sound per second in different media, solid, liquid, and gaseous, are as follows:—

Velocity of sound through gases at 0°.	Air	331m
	Oxygen	317
	Hydrogen	1270
	Carbonic acid	262
Velocity of sound through liquids	Water of the Seine at 15°	1437m
	Sea-water at 20°	1453
	,, at 23°	1160
	Ether at 0°	1159
Velocity of sound through solids	Tin	2498m
	Silver	2684
	Platinum	2701
	Oak, walnut	3440
	Copper	3716
	Steel, iron	5030
	Glass	5438
	Fir-wood	5994

CHAPTER III.

PROPAGATION OF SOUND.—PHENOMENA OF THE REFLECTION AND REFRACTION OF SOUND.

Echoes and resonances—Simple and multiple echoes; explanation of these phenomena—Laws of the reflection of sound; experimental verification—Phenomena of reflection at the surface of elliptical vaults—Experiments which prove the refraction of sonorous impulses.

WE shall learn hereafter that light and heat are propagated directly by radiation and indirectly by reflection. Moreover, when this propagation takes place through media whose nature and density differ, the direction of the luminous and calorific waves undergoes a particular deviation known to physicists as refraction.

The same phenomena of reflection and refraction occur in the case of sound as in that of heat and light, and they follow nearly the same laws.

That sound is reflected, when in being propagated by the air or any other medium it strikes against an obstacle, is a fact with which every one can make himself familiar by observation.

Echoes and resonances are phenomena due to the reflection of sound. When we stand in a large room, the walls of which are not covered with objects, such as curtains, which stifle sound, we notice that our voices are strengthened, and the sound of steps or of sonorous bodies is heard with great distinctness. In a still larger room words appear doubled, which often renders them difficult to be understood. This strengthening of sound, due to reflection from walls, &c., is what is called *resonance*.

If the distance from the observer to the reflecting surface exceeds 65½ feet (20 metres), he distinctly hears each word which he pronounces a second time: this is the simple echo. If each word is repeated two or three times, it is a multiple echo.

Let us understand the cause of these various phenomena.

However short the duration of a sound may be, the sensation which it induces in the ear of the listener remains a certain perceptible time, which is about $\frac{1}{10}$ of a second. During this time sound travels nearly 34 metres, so that if the distance A O from the observer to the reflecting surface (Fig. 97) is less than 17 metres, the sound of the word which he has pronounced has time to reach the wall and return to his ear before the sensation is entirely exhausted. The reflected sound will then be blended with that which he hears in a direct manner; and as a number of partial reflections are produced in different parts of the room, a confused murmuring will follow, which is called a resonance. The same explanation applies to the case of two or more persons occupying the same room and speaking either separately or together, and the resulting confusion of sound would become greater as the rapidity of utterance increased.

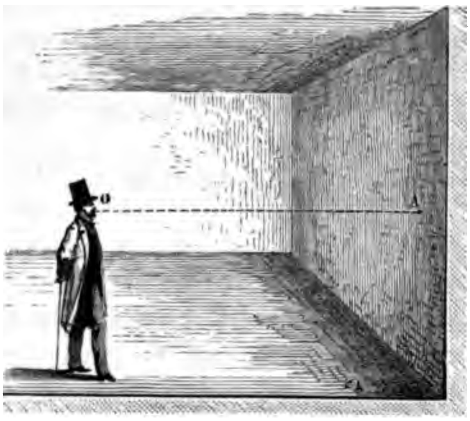

FIG. 97.—Reflection of sound. Phenomena of resonance.

If now the distance O A exceeds 17 metres, when the sound of the syllable is reflected to the ear the sensation is ended, and we hear a repetition more or less feeble of the direct sound. This is an echo. The greater the distance, the greater will be the number of syllables or distinct sounds. For example, let us suppose this distance to be 180 metres, and that in one second the observer pronounces three syllables, the words being *Answer me:* to go to the reflecting surface and to return, the sound takes a little over a second; the direct sensation is ended, and the ear hears for the second time, distinctly, *Answer me.* This is a simple echo.

A multiple echo occurs between distant parallel reflecting surfaces.

In this instance, the sound reflected by one of them is reflected a second time from another, and so on; but obviously, by these successive reflections, the sounds are weakened more and more. Edifices, rocks, masses of trees, even clouds, produce the phenomenon of echo. Among the most curious is the echo of the chateau of Simonetta, in Italy, which repeats the words spoken as many as forty times between the parallel wings of the edifice. We find in the *Cours de Physique* of M. Boutet de Monvel a curious fact, which visitors to the Pantheon can verify. In one of the vaults of this building, "it is sufficient for the guide who shows them to strike a sharp blow on the front of his coat to awaken in these resounding vaults a noise nearly equal to that of a cannon." This is a phenomenon of echo, and of concentration of sound.

In ancient and modern works a number of instances of multiple echoes are mentioned, the more or less surprising effects of which may be questioned, but they are all easily explained by the successive reflections of sound.

Such an one existed, it is said, at the tomb of Metella, the wife of Crassus, which repeated a whole verse of the *Æneid* as many as eight times. Addison speaks of an echo which repeated the noise of a pistol-shot fifty-six times. It was noticed, like that of Simonetta, in Italy. The echo of Verdun, formed by two large towers about 52 metres apart, repeats the same word twelve or thirteen times. The great pyramid of Egypt contains subterranean chambers connected by long passages, in which words are repeated ten times. Again, Barthius speaks of an echo situated near Coblentz, on the borders of the Rhine, which repeats the same syllable seventeen times. This had a very peculiar effect, because the person who spoke was scarcely heard, whilst the repetitions produced by the echo were very distinct sounds. Among echoes in England we may note one in Woodstock Park, which repeats seventeen syllables by day and twenty by night; while in the Whispering Gallery of St. Paul's the slightest sound is answered from one side of the dome to the other.

While living, for some years, on the sea-coast of Hyères, I heard a most magnificent echo: for a whole morning, reports of artillery fired from a vessel anchored in the roads were reflected from the sides of the mountains on the coast in prolonged echoes, which made me at first imagine the presence of a whole fleet; the effect was like that of thunderclaps. A single discharge seemed to last a minute.

The reflection of sound is subject to very simple laws, of which we will now give an outline. As we shall presently see, they result naturally from the vibratory movement which constitutes sound, and are also experimentally proved beyond all doubt.

To explain this, let us imagine for the present a sound-ray, like a ray of light, to start from a centre of disturbance and following a right line; when this ray comes in contact with a reflecting surface, let us call it an incident ray; then the reflected ray is the line along which the sound rebounds from this surface into the medium whence it came. The angles which the incident and reflected rays form with a line perpendicular to the surface at the point of incidence are called respectively the angles of incidence and reflection. These definitions being clearly understood, the following are the laws of the reflection of sound:—

First law.—The incident sound-ray and the reflected sound-ray are in the same plane with the line perpendicular to the surface at the point of incidence.

Second law.—The angle of incidence is equal to the angle of reflection.

The experimental proof of these laws is very simple. Let us place two metallic mirrors of a parabolic form—that is, obtained by the revolution of the curve called a parabola about its axis (Fig. 98)—face to face in such a manner that their axes coincide. The parabolic curve is necessary because it possesses, near its summit A, a focus F, to which all lines such as MZ, parallel to the axis AF, impinging upon different points of the parabola, are reflected. The rays proceeding from the focus and those parallel to the axis, form equal angles with the normals to the parabola, at every point, such as the point M. All rays parallel to the axis coming in contact with the parabola will be reflected to the focus at F.

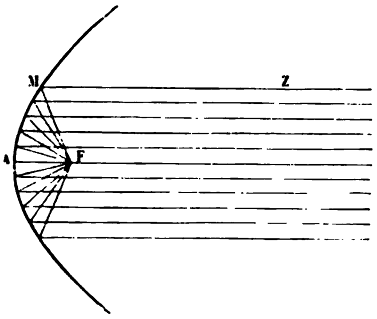

FIG. 98.—Property of the parabola.

Now, if a watch is placed in the focus of one of these parabolic mirrors, the sound-rays or sonorous waves produced by the ticking movement will be received on the mirror and reflected parallel to the axis; they then will strike the concave surface of the second mirror and be concentrated at its focus. The observer, who must employ a tube in order not to intercept the waves, will easily hear the sound of the watch if he places the extremity of the tube at the focus of the second mirror (Fig. 99). The sound is heard nowhere else, even by persons who place themselves near the space between the two mirrors, and at a short distance from the watch.

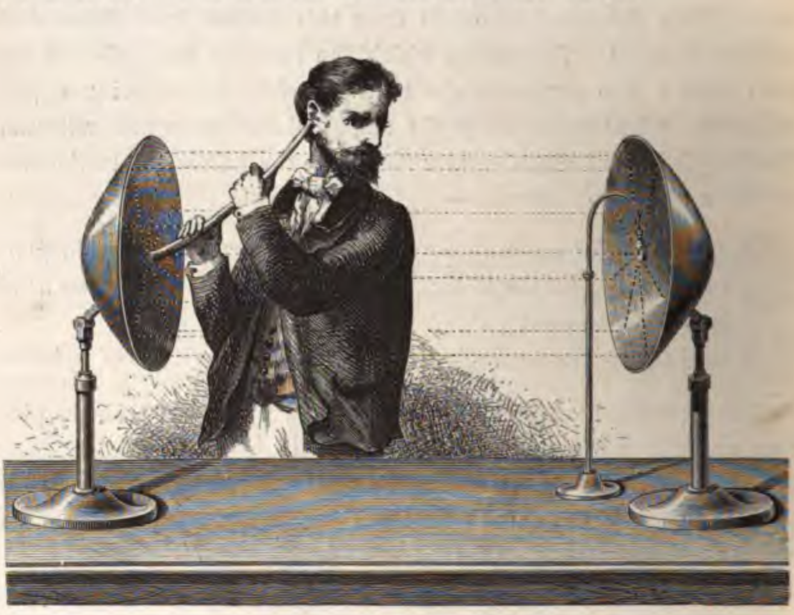

FIG. 99.—Experimental study of the laws of the reflection of sound.

The curve called an ellipse has two foci, and the rays sent from one are reflected to the other. A room with an elliptic roof should therefore produce the same phenomenon as the two parabolic mirrors; and this is confirmed by experiment. The Museum of Antiquities at the Louvre possesses a room of this kind, in which two persons placed at the opposite extremities of the room in the two foci, are able to converse in a whisper, utterly regardless of the presence of persons who are in other positions.

Reflection of sound is made use of in many instruments, which we shall have occasion to describe when speaking of the applications of physics to the sciences and arts.

Sound is propagated, as we have before seen, by all elastic media, but with varying velocities, which depend in a certain degree on the density of the medium. When sound passes from one medium to another, its velocity changes; and if it enters the second medium obliquely, a deviation of the sonorous wave results, which deviation brings the ray nearer the normal to the surface of separation of the two media, if the velocity is less in the second than in the first. When a ray enters a prism in which it is retarded, light undergoes a similar deviation, which was proved by experiment long before the true theoretical explanation was discovered; and as the phenomenon has been long known as refraction, the name of refraction of sound has been given to the similar deviation of the sound-waves. M. Sondhauss has placed the existence of this deviation beyond doubt by the following experiment. He made a lens of collodion, and filled it with carbonic acid gas. In this gas, the velocity of sound is

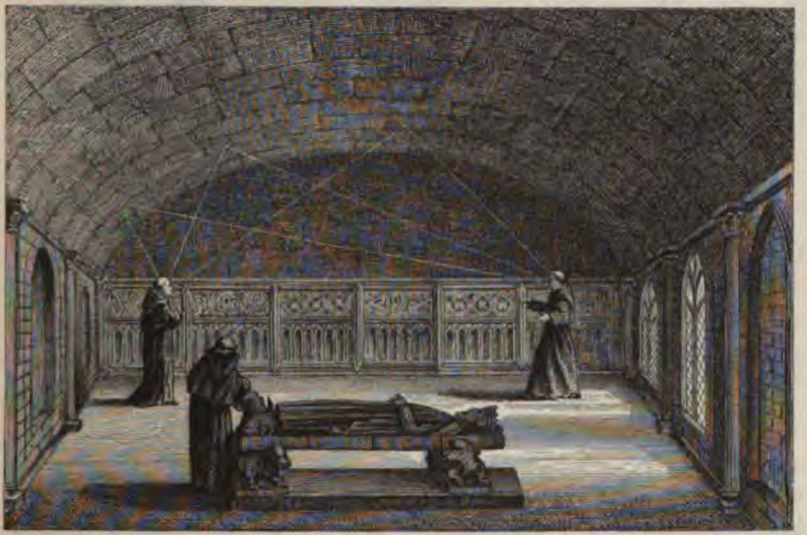

FIG. 100.—Reflection of sound from the surface of an elliptical roof.

less than in air. The sonorous waves which impinged upon the convex surface of the lens were refracted on passing through the gas, and, issuing on the opposite side, were brought to a focus. If a watch is placed in the axis of the lens on one side, there is on the axis at the other side a point where the ticking of the watch is heard distinctly, and better than in any other place. There is therefore an evident convergence of the sonorous waves towards the conjugate focus of the lens; and in this we have a proof of the refraction of sound.

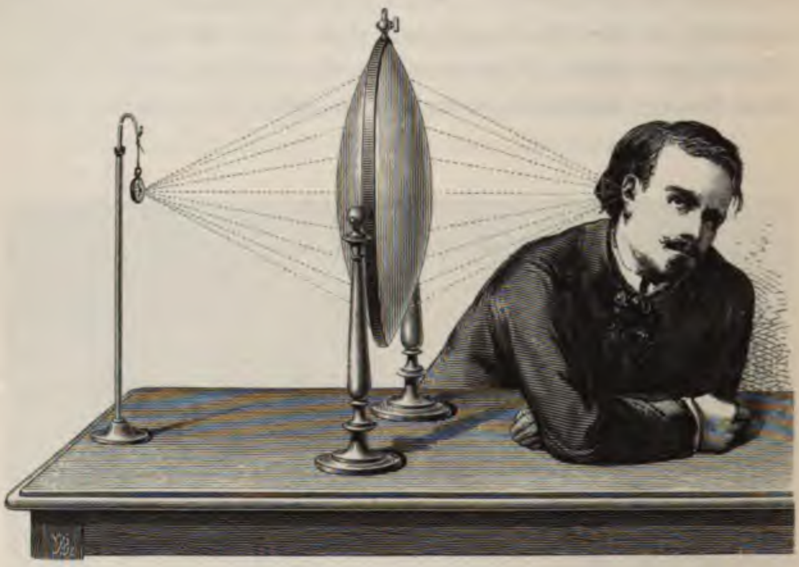
FIG. 101.—Sonorous refraction. M. Sondhauss's instrument.

CHAPTER IV.

SONOROUS VIBRATIONS.

Experiments which prove that sound is produced by the vibratory movement of the particles of solid, liquid, and gaseous bodies—Vibrations of a cord, rod, or bell—Trevelyan's instrument—Vibrations of water and of a column of air—Nature of sound: pitch, intensity, and clang-tint—The pitch depends on the number of vibrations of the sounding body; Savart's toothed wheel; Cagniard-Latour's and Seebeck's syrens—Graphic method—Variable intensity of sound during the day and night—Limit of perceptible sounds.

SOUND is a vibratory movement.

Sonorous bodies are elastic bodies, the molecules of which, under the action of percussion, friction, or other modes of disturbance, execute a series of alternating movements across their position of rest. These vibrations are communicated to surrounding gaseous, liquid, and solid media in every direction, and at last reach the organs of hearing. The vibratory movement then acts through the drum of the ear upon the special nerves of that organ, and produces in the brain the sensation of sound.

The existence of these sonorous vibrations may be proved by very simple experiments.

If we take a violin string and stretch it at its two extremities upon a surface of a darkish colour—this condition is realized in stringed instruments—and if sound is then produced by the aid of a transverse bow, or by plucking the string from its position of rest, the string will appear to expand from its two extremities to the middle, and will here present an apparent enlargement, due to a rapid alternating movement across its normal position. The string is seen at the same time, so to speak, in its extreme and in its mean positions, in consequence of the persistence of luminous impressions on the eye. (Fig. 102.)

Instead of a string, let us imagine a cane or a flexible metallic rod fixed at one of its ends. On moving it from the position of rest, it undergoes a series of oscillations, the amplitude of which continues to decrease until at last the motion ceases. During the vibrations of the rod, a sound is heard which decreases and ends with the movement. (Fig. 103.)

The rim of a glass or metal bell, rubbed with a bow, emits sounds which are frequently very loud.

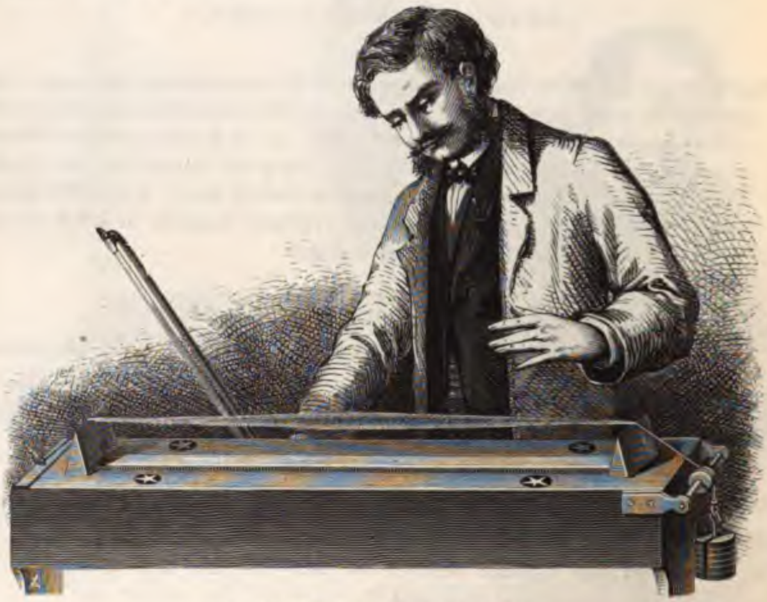

FIG. 102.—Vibrations of stretched string.

The existence of the vibrations which induce these sounds is easily proved. If we take a rod of metal the point of which grazes the rim of a bell without touching it, when the bell vibrates it strikes the glass with sharp and repeated strokes, and the noise thus produced is quickly distinguished from the sound produced by the bell. (Fig. 104.) The ball of a pendulum is also sent back with force, and oscillates during the time that the sound continues. In the same way a metallic ball placed in the interior of a bell moves about when this latter is caused to resound, as in Fig. 105, and thus proves the existence of the vibrations with which the molecules of the sounding body are animated.

Trevelyan's instrument, of which we have spoken before, and by the aid of which sounds are obtained by the contact of two solid bodies at unequal temperatures, also proves the existence of the vibrations which produce sound. If we place a bar terminated by two knobs on the heated metal, the weight of this bar renders its vibrations slower, and we can watch the alternating motion of the rod and knobs. (Fig. 106.) Tyndall has devised an ingenious way of showing these vibrations. He fixes at the centre of the vibrating metal a small disc of polished silver, on which a beam of the electric light is cast. The light is reflected from the mirror to a screen, and as soon as the warm metal comes in contact with the cold lead, the motion of the spot of light is apparent on the screen. When we study the effects of heat, we shall observe that the cause of the oscillations of the metal, in Trevelyan's instrument, is the alternate dilatation of the lead at the points of contact of the warm metal; this

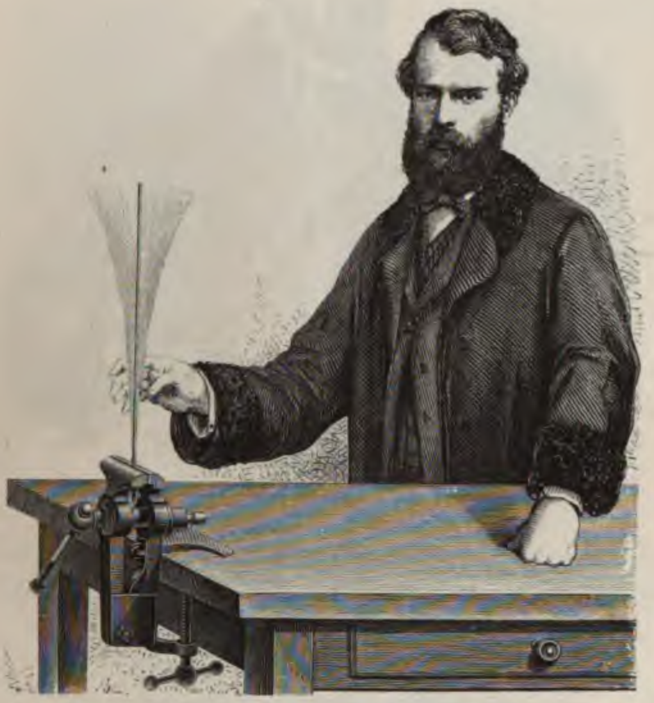

FIG. 103.—Vibrations of a metal rod.

dilatation produces small nipples, which, by their rising, throw the heated rocker from side to side, and this alternating motion takes place with sufficient quickness to produce vibrations in the air, which reach our ears as sound. (Fig. 107.)

We shall presently see other proofs of the existence of these molecular movements, when we describe the processes used to measure the number of vibrations produced by sounding bodies. When a solid body produces a sound, the vibratory movement is readily rendered perceptible by the trembling communicated to the hand on touching it. The vibrations of liquids and gases, when they produce or transmit sound, can also be rendered visible.

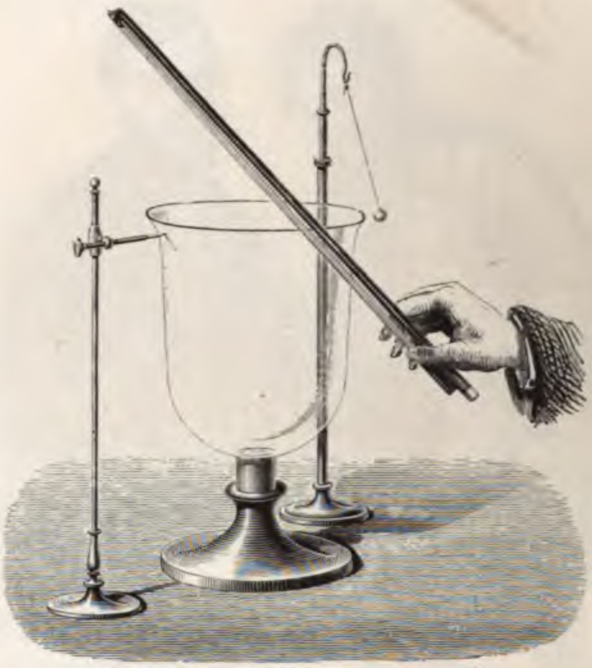

FIG. 104.—Proof of the vibration of a glass bell.

A glass goblet, half filled with water, vibrates like the glass bell of which we have spoken, when the edges are rubbed either with the wet finger or with a bow. (Fig. 108.) We observe also on the surface of the liquid a multitude of waves, which are divided into four and sometimes into six principal groups, and these waves become more serrated as the sound becomes more sharp. If the sound is greatly intensified, the amplitude of the vibrations becomes so great that the water is jerked from each section in the form of fine rain. Lastly, if we connect a sonorous tube with a pair of bellows, we can prove the vibration of the interior column of air in the following manner. A

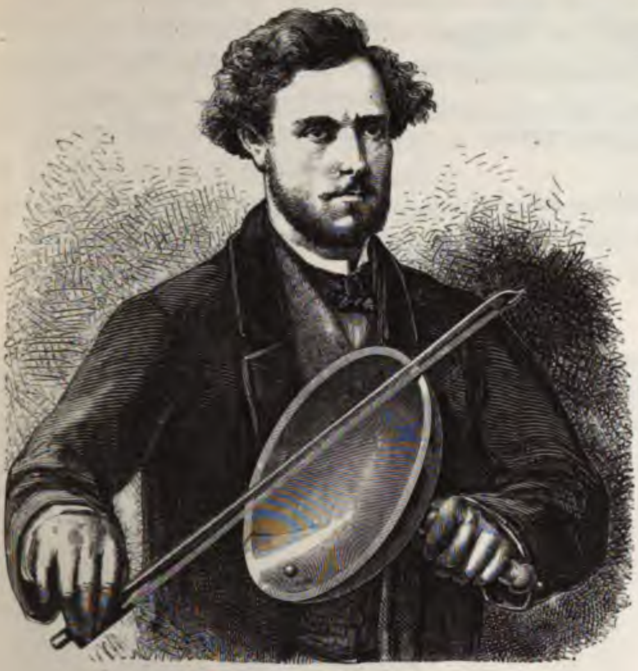

FIG. 105.—Vibrations of a metal clock bell.

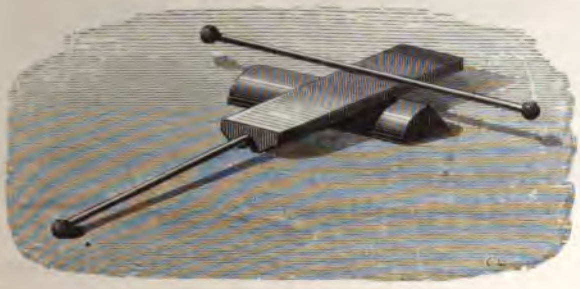

FIG. 106.—Trevelyan's instrument.

frame covered with a membrane is suspended by a string in the interior of the tube; when the tube is caused to emit a sound, we perceive the grains of sand which previously were at rest on the membrane to be jerked up; thus proving that the vibrations of the gaseous column have been transmitted to the membrane itself and to the light grains which rested upon it. (Fig. 109.)

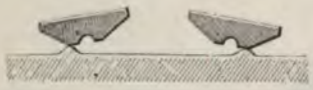

FIG. 107.—Trevelyan's instrument. Cause of vibratory movements.

Vibrations transmitted by the air sometimes possess great power. Window-panes shake and are sometimes even broken in the neighbourhood of a very loud report, such as that of a cannon.

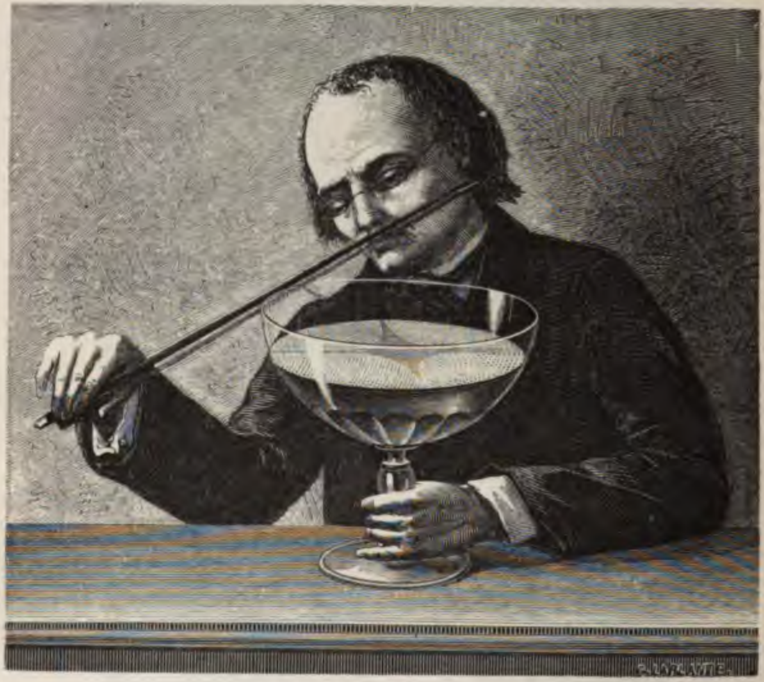

FIG. 108.—Vibrations of liquid molecules.

We have thus demonstrated by experiment the fundamental fact that sound results from a vibratory motion produced by the molecules of solid, liquid, or gaseous elastic bodies, which vibrations are transmitted to the organ of hearing by the intervention of different media which extend between the sonorous body and the ear. We now understand why sound is not propagated in a vacuum. The bell struck under the receiver of the air-pump vibrates freely, but its vibrations are no longer transmitted, or at least are very imperfectly transmitted, by the cushion which supports the instrument, and by the small quantity of air which always remains in the most complete vacuum which it is possible to produce by an air-pump.

We shall endeavour shortly to give some idea of the nature of sonorous vibrations, and of the successive condensations and dilatations which result from their propagation through elastic media, in order to explain how the laws of acoustics, which all our observations and experiments confirm, have been proved by theory. For the present we will continue to describe phenomena.

Sounds are distinguished from each other by several characteristics, which we will next describe.

The most important of these, not so much from a physical as from a musical point of view, is the "pitch," that is to say, the degree of acuteness or of graveness of sound. Every one can distinguish acute from grave sounds, whatever may be the sonorous body which produces them. Two sounds of the same pitch are said to be in unison. The intensity of a sound is quite different from the pitch; the same sound can be loud or feeble, without ceasing to have the same degree of acuteness or of graveness.

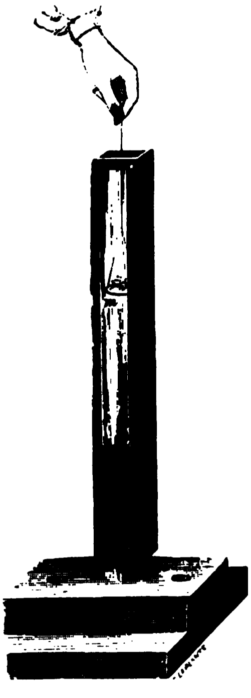

FIG. 199.—Vibrations of a gaseous column.

Lastly, different sounds are distinguished from each other by their quality, or "clang-tint," as Tyndall proposes to call it (*timbre*, French; *klangfarbe*, German). When a flute and a violin, for example, emit the same musical sound with equal force, the ear will not fail to distinguish a difference between the two sounds, such as it will be impossible to confound them. It is this peculiar quality by which we recognize the sound of a voice which is familiar to us.

The pitch of a sound depends on the greater or less number of vibrations which are produced by the sonorous body and propagated through the media by the help of which sound is conveyed. This number increases as the sound becomes more shrill, and we shall now see by what means philosophers have proved this important fact, and how they have counted these movements, which the eye or our other senses could only observe in a more or less confused manner.

The toothed wheel invented by Savart enables the number of vibrations which produce a given note to be determined. The sound —which to give us a musical note must fall with regular pulsations on our ears, irregular pulsations only producing *noise*—is produced in this instrument by the teeth of a rapidly revolving wheel striking against a piece of card. When the velocity of the wheel is small, we only hear a series of separate strokes, the whole of which, properly speaking, do not produce a musical note, and the pitch is consequently absent. But in proportion as the velocity of the wheel increases, the multiplied vibrations of the card transmitted to the air produce a continuous and regular *note*, the acuteness of which is greater as the velocity of the wheel increases. An indicator is fixed to the toothed wheel, which gives the number of revolutions which it

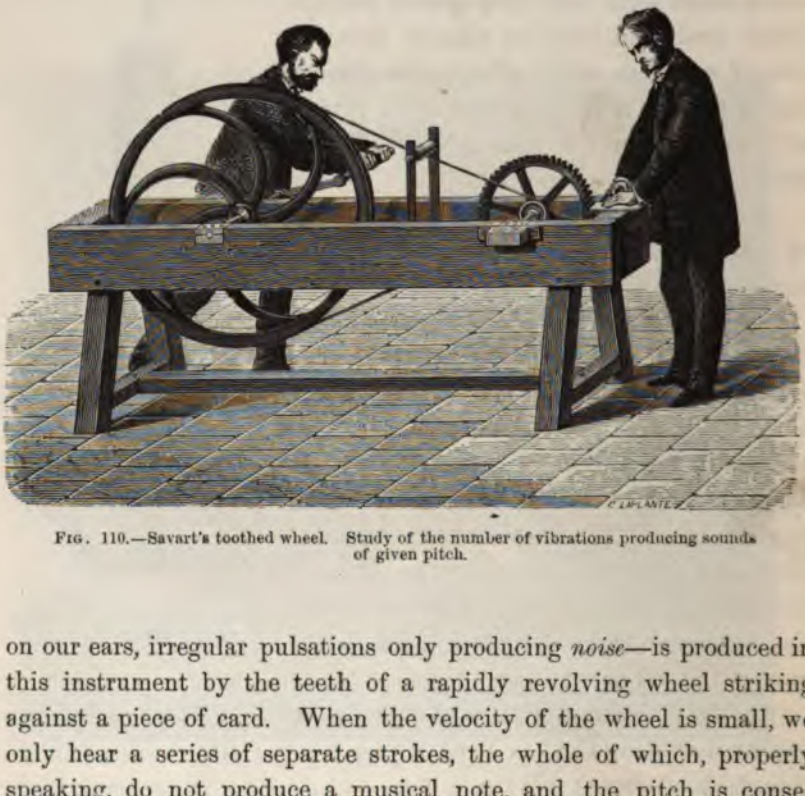

FIG. 110.—Savart's toothed wheel. Study of the number of vibrations producing sounds of given pitch.

makes in a second: this number, multiplied by that of the teeth, gives the half of the total number of vibrations; for it is clear that the card, at first bent from its position of rest, afterwards returns on itself, and produces two vibrations for each tooth which strikes it.

Savart obtained with a wheel furnished with 600 teeth as many as forty revolutions a second, and consequently 48,000 vibrations in the same time; which corresponds, as we shall see further on, to a sound of extreme elevation or acuteness.

The Syren, invented by Cagniard-Latour, is also used to measure (even with greater precision than the toothed wheel of Savart) the vibrations of a given sound.

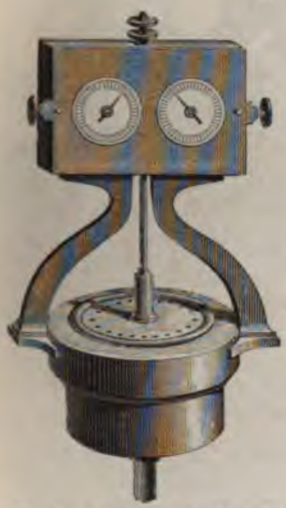

FIG. 111.—Cagniard-Latour's Syren.

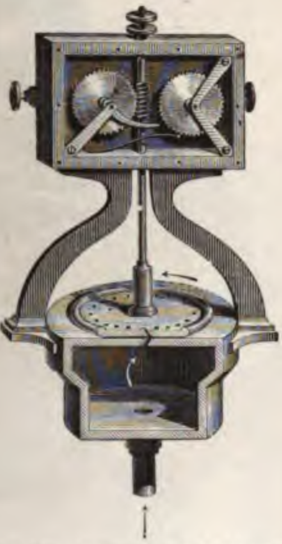

FIG. 112.—Interior view of the Syren.

In this ingenious instrument the sound is produced by a current of air from a pair of bellows, which air passes through a series of holes placed at equal distances round two metallic plates, one being fixed and the other moveable. When the holes correspond, the current of air passes, and its force of expulsion acting on the oblique channels which form the holes, gives movement to the upper plate. This act causes the coincidence to cease, then establishes it again, then stops it, and so on, the result being the production of a series of puffs which produce vibrations, increasing in rapidity, in the air.

If there are twenty holes, there are forty vibrations for each turn of the plate; so that in counting the number of revolutions which are effected for a given sound in a second, the total number of vibrations can be easily calculated. The axis of the moveable plate works, by means of an endless screw, in a toothed wheel, the number of teeth being equal to that of the divisions of a dial outside. When the wheel advances a tooth, the needle marks one division; so that the number of divisions passed over by the needle gives that of the turns, and then, by simple multiplication, that of the sonorous vibrations. At the end of each revolution, a catch turns a second wheel one division; so that if the first wheel has a hundred teeth, the needle of the second dial indicates hundreds of turns.

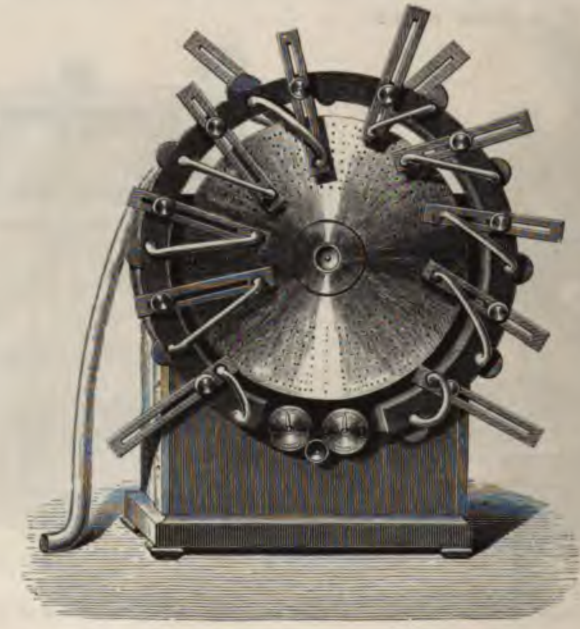

FIG. 113.—Seebeck's Syren.

The indicator is disposed so that it only moves at will; that is to say, when the attained velocity has produced the note which we desire to examine as regards the number of vibrations which constitute it. The chief difficulty is to maintain a constant velocity, so as to have a note of invariable pitch for as long a time as possible.

The syren also acts in water; in this case the liquid rushes through the holes under the pressure of a lofty column of water, and thus produces vibrations. The sound which follows proves that liquids enter into direct vibration, like gases, without sound being communicated to them by the vibrations of a solid. The name *syren* comes from the circumstance that the instrument sings under water like the enchantresses of the fable.

Seebeck's syren, represented by Fig. 113, is constructed in quite a different manner, but the principle is the same, viz. that the note is produced by the regular passage of air in puffs through the holes ot a disc. The disc is caused to rotate by clockwork, and the velocity of its rotation is measured by an indicator. Around it is a wind-chest communicating with a pair of bellows: and it acts as distributor of the current which is transmitted by caoutchouc tubing to any series of holes in the disc which the experimenter may wish to use.

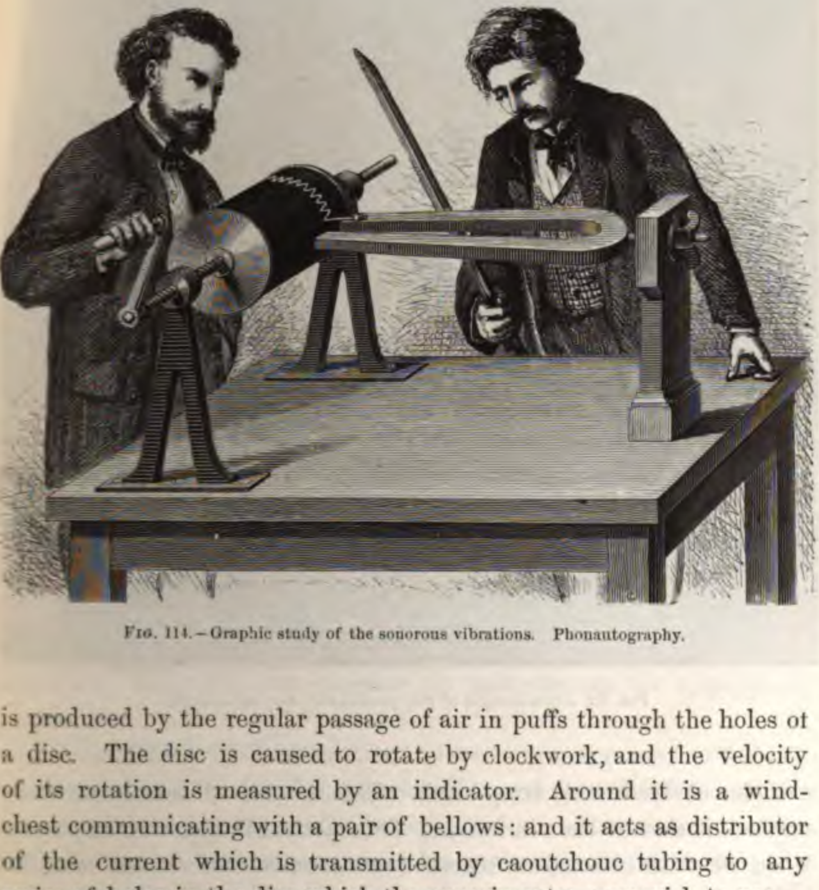

FIG. 114.—Graphic study of the sonorous vibrations. Phonautography.

A great number of experiments can be made with this syren by varying the number and distribution of the holes in different discs

Lastly, certain graphic methods, recently invented, but the first idea of which is due to Savart, allow us to determine with exactitude the number of sonorous vibrations.

A tuning-fork, or metallic rod, furnished with very fine points, may be caused to trace undulating lines on the surface of a turning cylinder covered with lamp-black. The number of sinuosities thus marked is that of the vibrations. This method is specially employed when we wish to compare together two sounds with respect to their pitch. For example, we fix on a tuning-fork the point which traces the sinuous lines, and on a second tuning-fork the plate covered with lamp-black where these lines are traced. Then causing the two tuning-

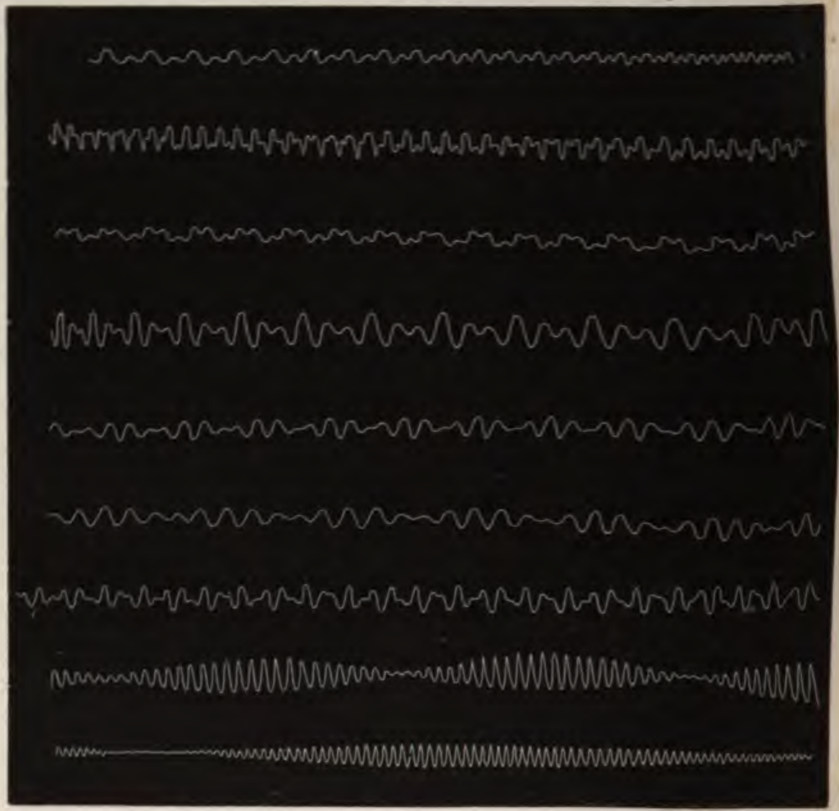

FIG. 115.—Combination of two parallel vibratory movements.

forks to vibrate simultaneously, the sinuous line obtained will be evidently the result of the combination of two vibratory movements, parallel if the two tuning-forks vibrate in the same direction, rectangular if they vibrate at right angles. Figs. 115 and 116 are facsimiles of proofs obtained by these two combinations for various musical intervals.

The various experiments which we have just described tend to prove that the pitch of a sound depends only on the number of vibrations executed by the sonorous body in a given time. The intensity of the sound, whether strong or feeble, undergoes no change; the nature of the sonorous body and the particular quality, which is called the clang-tint, has likewise no influence on the number of vibrations.

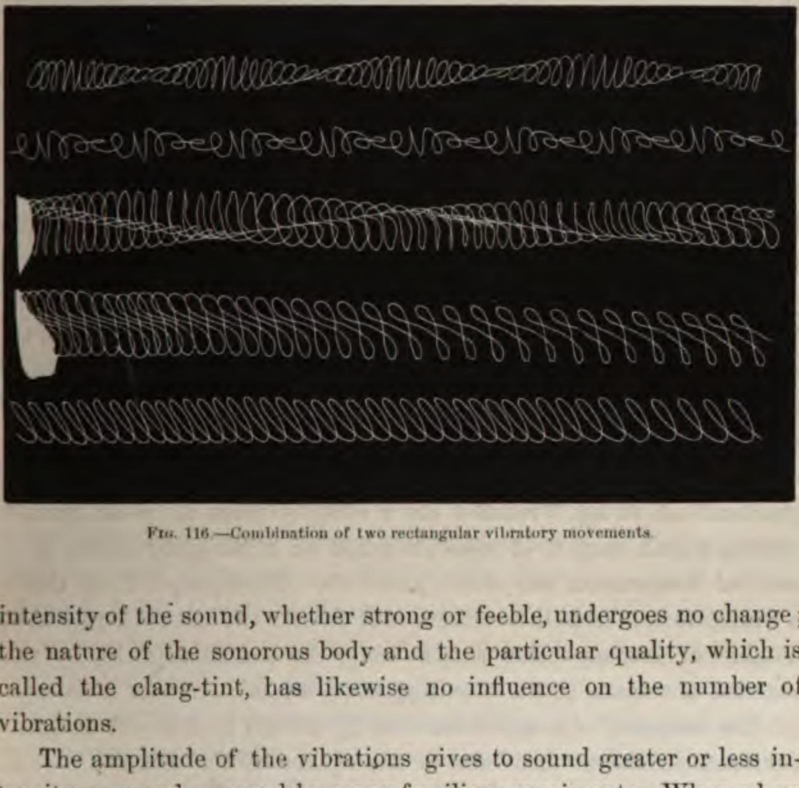

FIG. 116.—Combination of two rectangular vibratory movements.

The amplitude of the vibrations gives to sound greater or less intensity, as may be proved by many familiar experiments. When a bow is drawn across the string of a violin, or of any other similar instrument, the sound decreases in proportion as the vibrations of the cord is less considerable. The more vigorous the friction of the bow, the more marked are the oscillations, and the intensity of the sound is greater. Since, then, its pitch is not modified, it must be concluded that the number of vibrations is not altered, although the vibrations of the cord are made with greater rapidity, the path traversed in an equal time being greater when the amplitude is itself greater.

When an elastic body produces a sound, the molecules of which it is composed are not equally moved from their positions of rest: there are some even, as we shall soon see, which remain in a state of repose. A bell, for example, when struck by a hammer, is caused to become elliptic, first in one direction, then in another at right angles to the first. The zones of metal at its base execute slower vibrations and of greater amplitude than the zones near the top. But the solidity of the zones or rings produces a compensation between these amplitudes and the different velocities, and there results for the sound produced a mean pitch and intensity which depends on the dimensions and nature of the metal of which the bell is formed. This indicates an evident analogy between these vibrations and the oscillations of the compound pendulum, the length of which we have seen is a mean between the lengths of the oscillations of a series of simple pendulums of different lengths.

The above remarks relate only to the intrinsic intensity of sound which depends on the amplitude of the vibrations executed by the moving molecules. But as sound is transmitted to our ear through the medium of the air, the intensity will be greater as the volume of air displaced is at the same time more considerable, and consequently the dimensions of the sonorous body will themselves be greater. A string stretched on a straight piece of wood gives a weaker sound than if it were stretched on a sounding-board, as in musical instruments, the violin, piano, &c. Most people know that if a tuning-fork is caused to vibrate first in the air, and then placed on a table or on any other elastic body, the sound acquires, by this increase of volume of the vibrating body, a much stronger intensity.

The intensity of a sound received by the ear at different distances decreases in the inverse ratio of the square of the distance. Thus, at 10 metres the intensity is four times greater than at 20 metres, nine times more than at 30 metres, &c. provided that the circumstances of the propagation remain the same, and that reflecting bodies are not present to strengthen the sound. Hence it follows that if two sounds, one being four times louder than the other, are produced at two different stations, the observer who is placed at one-third of the distance which separates them from the weakest, will believe that he hears two sounds of the same intensity.

The reason is as follows:—Sonorous waves are propagated spherically around the centre of disturbance, hence the vibrations put into movement successive spherical shells, the volume of which is in proportion to the surface, and increases therefore as the squares of their distances from the centre. Since the masses of the dispersed layers are greater and greater, the movement which is communicated to them by the same force must diminish.

In columns, or cylindrical tubes, the successive impulses are equal: the intensity of the propagated sounds must therefore remain nearly the same, whatever the distance may be. This is also confirmed by observation. M. Biot, in the experiments by which he determined the velocity of sound in solid bodies, proved the fact, that the sound transmitted by the air in the pipes of the aqueducts of Paris was not sensibly enfeebled at a distance of nearly a kilometre. Two persons speaking in whispers could easily hold a conversation through these pipes. "There is only one means not to be heard," says M. Biot,—"not to speak at all."

Speaking-trumpets and acoustic tubes are applications of this property which we have just described. We shall speak of some of these hereafter.

This property of cylindrical sound channels explains certain acoustic effects shown in rooms or vaults of different monuments. The mouldings of the vaults or walls form channels where the sound is propagated with great facility and without losing its first intensity. In Paris, there are two rooms of this kind; one square and vaulted, situated at the Conservatoire des Arts et Métiers; the other, of a hexagonal form, is in the Observatory of Paris: in both, the angles, being joined by an arch, form deep furrows, which eminently conduce to the conduction of sound without enfeebling it. Two persons also can converse in whispers, from one corner to the other, without the auditors placed between them being able to hear any of their conversation. In St. Paul's Cathedral the gallery of the dome affords a similar instance; the gallery of Gloucester is another example, the cathedral of Girgenti in Sicily, and the famous grotto of Syracuse, at the present day known as the "Grotta della Favella," and in olden times as that of the Ear of Dionysius. It was in the ancient Latomiæ, or quarries of Syracuse, that the Tyrant had contrived a secret communication between his palace and the caverns where he kept his victims, taking advantage of the peculiar arrangement of the grotto to listen to their conversation.

The intensity of the sound perceived varies according to the density of the medium which propagates it. We have seen this already, in the experiment made under the receiver of the air-pump: the sound of the bell is enfeebled in proportion as the vacuum is increased. The contrary would take place, as Hauksbee has proved, if the air were compressed in the receiver wherein the sonorous body is placed. Persons who ascend into the high regions of the air, either on mountains or in balloons, all prove the gradual decrease of sound due to the diminution of the density of the atmospheric air. In water, the sonorous waves are transmitted with greater intensity than in air, if the sonorous body vibrates with the same energy in both media. In solid bodies of cylindrical or prismatic form, sound is propagated without being enfeebled as much as in the air or other gases. We most of us know the experiment of placing the ear at the end of a long wooden beam, when we can hear very distinctly the slightest noise—for example, that produced by the friction of a pin. Savages place the ear near the ground to hear distant sounds which could not be transmitted by the air through the same distance.

It is a fact generally known and of easy observation, that sound is heard further during the night than during the day. This increase of intensity is attributed to the homogeneity of the strata of air and their relatively calm condition, which allows the sonorous waves to be propagated without losing their amplitude by reflection. It must also be remembered that during the day various noises conduce at the same time to make an impression on the ear, each of which must be less easily distinguished. According to the observations of Bravais and Martins, the distance to which a sound reaches depends also on the temperature of the air: this distance is greater during the cold of winter, in snowy regions of the pole, or high mountains. Here it is to the homogeneity of the air rather than to its density that we must attribute the cause of this fact, for on the summit of mountains the density of the air is less than in the plains. The intensity of transmitted sound certainly depends on the state of repose or agitation of the air. In calm weather it is distinctly heard at great distances: wind enfeebles sound even when it comes from the point where the body gives out the sounds. The direction of the vibrations, that is to say, the manner in which the auditor is turned relatively to the point whence the sound starts, has also a great influence on its intensity. When we hear the flourish of a hunting horn, if the performer turns the mouth of his instrument in different directions the intensity varies, so that it seems sometimes to get nearer to and sometimes further from the place where the auditor is.

The circumstances which tend to modify the intensity of sound are therefore very varied. It is therefore difficult to determine the greatest distance to which it can reach. In the remarkable examples which are quoted, of sounds heard at considerable distances, it is probable that it is the ground rather than the air which serves as a vehicle to the sonorous vibrations. We have already quoted Humboldt on the subject of the reports produced by earthquakes and volcanic eruptions, which are propagated to distances of 800 to 1,200 kilometres. Chladni relates many facts which prove that the noise of cannon is often heard at very great distances; at the siege of Genoa it was heard at ninety miles from Italy; at the siege of Mannheim in 1795, at the other side of Souabia, at Nordlingen and Wallerstein; at the battle of Jena, between Wittenberg and Treuenbrietzen. "I have myself heard," he says, "cannon-shots at Wittenberg at seventeen German miles, not so much by the air as by the disturbance of solid bodies, by placing the head against a wall."

Nevertheless, sound, such as the rolling of thunder and the detonations of meteors, which sometimes burst at enormous heights, is often propagated to a great distance by the air. Chladni mentions certain meteors the explosion of which was not heard until ten minutes after the luminous globe was seen: this supposes a height of not less than 200 kilometres. The bolide observed in the middle of France on the 14th of May, 1864, presented the same peculiarity, and the observers calculated four minutes between its appearance and the perception of the noise of its report. "In order to have an explosion," says M. Daubrée, writing on this subject, "produced in strata of air sufficiently rarefied to give place on the surface of the earth to a noise of such intensity, and over a horizontal extent so considerable, we must admit that its violence in high regions exceeds all that we know." Unless indeed, this is an effect of repercussion of the sound on strata of air of unequal density, analogous to the rolling of thunder in storms.

We know but little at present of the production of the indefinite varieties of tones. We shall speak hereafter of recent researches on this subject; the phenomena which we must first notice are necessary for the right understanding of the proposed explanations.

Experimenters have tried to determine the limit of perceptible sounds; but it is clear that this limit depends partly on the sensibility of our organs. The most grave sound appears to be that which is produced by a sonorous body executing thirty-two simple vibrations in a second. Savart found for the most acute, 48,000 vibrations. But M. Despretz made a series of tuning-forks the sounds of which were strengthened by resonant boxes, and he at last distinguished the sound of most extreme sharpness which a tuning-fork can produce to be caused by 73,700 vibrations per second. We remember assisting at the experiments of this learned philosopher. Such shrill sounds produce in the organ of hearing a sensation almost doleful.

CHAPTER V.

LAWS OF SONOROUS VIBRATIONS, IN STRINGS, RODS, PIPES, AND PLATES.

Experimental study of the laws which govern the vibration of strings—Monochord or Sonometer—Nodes and ventral segments; harmonics—Laws of the vibrations of sonorous pipes—Vibrations in rods and plates—Nodal lines of square, round, and polygonal plates.

IN the present day, the art of music is so generally understood that such of our readers as have knowledge of it, or who have seen it produced, know the mechanism of stringed instruments, such as the violin.

Four strings of unequal diameter and of different textures are stretched by the aid of pegs between two fixed points, and when caused to vibrate, either by the hand or by drawing a bow across them, they produce sounds of different pitch. The sounds produced by the open strings (that is to say, when they vibrate in the whole of their length) must possess a certain connection of tone between them, of which we shall soon speak. When this connection is destroyed, the instrument is not in tune. What does the musician then do? By screwing and unscrewing the pegs he stretches more or less those of the strings which do not give out the desired sounds: as he tightens them the sound becomes more acute; and, on the other hand, if he loosens them it becomes more grave. But four sounds would not be sufficient to provide all the varied notes of a piece of music. The performer multiplies the number at will, by placing the fingers of his left hand on certain points of each of the strings. In doing this he reduces to different lengths the portions of these strings which the bow causes to vibrate.

These facts show that there exist certain relationships between the pitch of the different sounds given out by the instrument and the length, diameter, tension, and substance of the strings; as the pitch itself depends on the number of the vibrations executed, it necessarily follows that this number is connected by certain laws with the elements already enunciated. Some of the most important were noticed by the ancient philosophers, and particularly by the Pythagoreans. But it is to the geometers of the last century, amongst whom are the illustrious names of Taylor, Bernouilli, D'Alembert, Euler, and Lagrange, that we owe the complete demonstration deduced from purely theoretical grounds. The exactitude of the calculations has been confirmed by experiments.

We will now endeavour to explain these laws. In the present day they are readily proved by means of a particular instrument, called a monochord or sonometer, to which is attached an apparatus which enables us to ascertain the numbers of vibrations produced. The sonometer, or monochord (Fig. 117) is formed of a box of fir-wood to strengthen the sound; above this box one or several strings are fixed at their extremities by iron pins, and stretched by weights which serve to determine the tensions of each of them. A divided scale beneath the strings shows the lengths of the vibrating parts, which can be altered at will by the aid of a moveable bridge which moves along the scale under the strings.

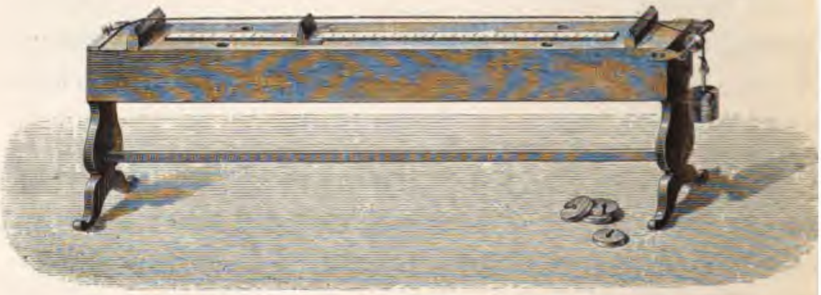

FIG. 117.—Sonometer.

Let us take a string of catgut or metal, and stretch it by a weight sufficient to cause it to produce a perfectly pure sound, of a pitch appreciable to the ear; and let us suppose that its total length measured by the scale is 1·20 metre, and that the sound which it gives out corresponds (as verified by the Syren) to 440 vibrations a second. Let us place the moveable bridge first at the half, then at $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{12}$ of the total length; and in each of these successive positions let us cause the shortest portion of the string to vibrate. Measuring the different sounds obtained, we shall find the following number of vibrations a second: 880, 1,320, 1,760, and 5,280.

It only remains for us now to compare the numbers which indicate the different lengths of the string, and those which indicate the number of vibrations, to understand the law.

Length of string . . .	120	60	40	30	10
	or 1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{12}$
Number of vibrations .	440	880	1,320	1,760	5,280
	or 1	2	3	4	12

Is it not evident from this experiment that the number of vibrations goes on increasing, so that their ratios are precisely the inverse of those which the lengths of the strings form between themselves? Such is the first law of vibrating strings.

Now, without altering the length, if we stretch the same string by different weights, and compare the sounds obtained, we shall find, for the numbers of double, triple, or quadruple vibrations, the tensions of the strings are 4, 9, 16, &c. times greater. The numbers of vibrations follow the order of the simple numbers, the weights or tensions follow the order of the squares of these numbers. This is the second law.

The strings are of cylindrical form. Let us change the diameter of these cylinders, and compare the sounds produced by two strings of the same substance, stretched by equal weights and of equal length, but of different diameters. This comparison will be easy with the help of the sonometer. It is then found that the number of vibrations of these sounds decreases when the diameters of the strings augment, and become precisely 2, 3, 4 . . . . times less, when the diameters are 2, 3, 4 . . . . times greater.

This is the third law of the transversal vibrations of vibrating strings.

There is a fourth law, which, like the others, may be proved by means of the sonometer, and which relates to the density of the substance of which the vibrating string is composed. Two strings, one of iron, the other of platinum, of the same length and diameter, are stretched on the sonometer by equal weights. The sounds which they will give out will be the more grave as the density is greater, so that the iron string will give the acute and the platinum the more grave sound; the ear will be sufficient to judge of these differences. Now, if we measure the exact numbers of vibrations which correspond to the two sounds obtained, we shall find:—

For the iron	1,640
For the platinum	1,000

We not only speak here of the numbers, but of their relationship. Now, if we multiply each of these numbers by itself, if we take the square, we find 2,699,600 and 1,000,000, which indicates precisely in an inverse order the densities of the metals, platinum and iron. The density of iron is 7·8, that of platinum 21·04, and these densities are related as 1·00 is to 2·69. Such is the law: other things being equal, the squares of the number of vibrations are in the inverse ratio of the densities of the substances of which the vibrating strings are formed.

In the preceding remarks we have spoken only of the transverse vibrations of strings, that is to say, of the sounds which follow either from the plucking or removing a string from its position of rest, or from drawing a bow across it. A string rubbed lengthways with a piece of cloth powdered with resin also emits a sound, but this sound is much more acute than when it vibrates transversally, so that the number of the longitudinal vibrations always exceeds that of the transversal vibrations. As this method of causing strings to vibrate is not employed, we need not enlarge on this subject. But we must not conclude the subject of vibrating strings without mentioning a phenomenon of great interest: we speak of *nodes* and *ventral segments*, and the particular sounds which musicians and physicists call *harmonics*. Let us imagine a string stretched on the sonometer, or on any musical instrument, and let us fix it by placing our finger at the middle, and then cause one of the halves to vibrate by means of the bow: the sound produced will be, as we shall hear, more acute than the fundamental sound—that is, the sound given out by the string when its whole length vibrates—the number of the vibrations being doubled. Musically speaking, this is the octave of the fundamental note. But it is remarkable that the two halves of the string vibrate together, which may be proved, first by putting crosswise on the centre of that half of the string which remains free some little paper riders, which jump about and fall directly the sound is produced; secondly, by proving to the eye the existence of an enlargement in the two halves of the string (Fig. 118); for if we remove our finger without stopping the movement of the bow, we notice that the sound continues, as well as the division of the string into two parts, which vibrate simultaneously.

Let us make a second experiment, and place the finger on a portion of the string one-third of its entire length from the nearest bridge, continuing to draw the bow across the smallest portion (Fig. 119).

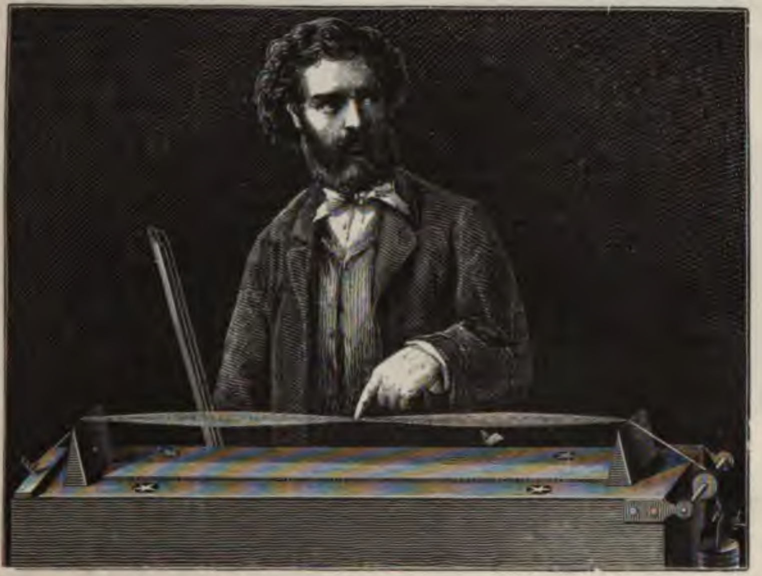

FIG. 118.—Harmonic sounds. Nodes and ventral segments of a vibrating string.

The sound is still more acute, and we observe the whole string to be divided into three equal parts, vibrating separately: this can be proved by placing the riders at the points of division, as well as at the middle of each third of the string. The first remain immoveable, the others are thrown off; which proves the existence of immoveable points or *nodes*, and vibrating parts or *ventral segments*. Against a black ground, the nodes and ventral segments can be clearly distinguished. The first show the white string reduced to its proper thickness; the others the swellings similar to those which we have before noticed at the centre of a string vibrating as a whole.

A string can thus be divided into 2, 3, 4, 5 . . . . equal parts, and the sounds, gradually increasing in acuteness, which they then produce, are called *harmonics*. Practised ears can distinguish some of the harmonic sounds which are produced simultaneously with the fundamental sound of a string, which proves that the division of the string into vibrating portions takes place even when the contact of a point is not the determining cause. We shall see further on the position which these different sounds occupy in the musical scale. Studied by the help of the graphic method, the sonorous vibrations which engender harmonics show that they result from compound sounds superposed on the simple vibrations (Fig. 120). Nodes and ventral segments are not peculiar to vibrating strings: we shall find them also in the columns of air which vibrate in the interior of pipes; we shall also observe them in plates and membranes.

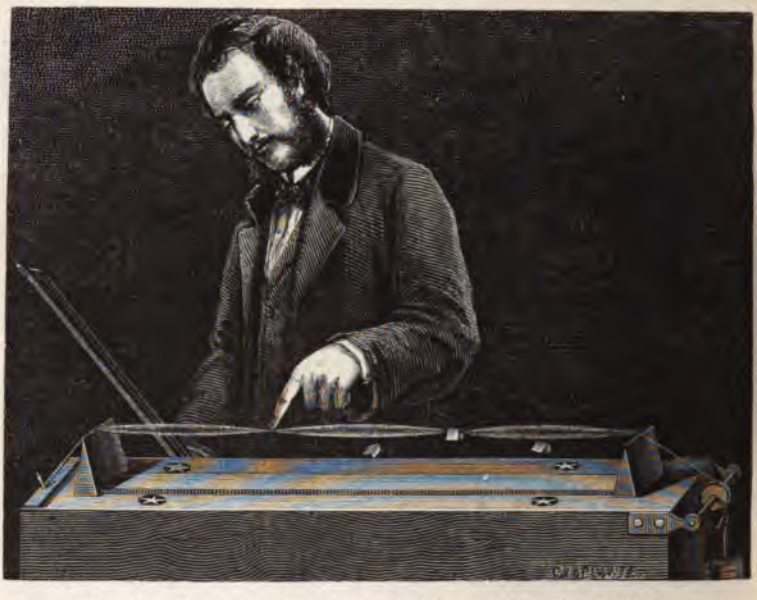

FIG. 119.—Harmonics. Nodes and ventral segments of a vibrating string.

Musical instruments called *wind-instruments* are formed of solid pipes, sometimes prismatic and sometimes cylindrical, some straight, others more or less bent. The column of air which these instruments enclose is caused to vibrate by means of a mouthpiece, the form and disposition of which varies according to the nature of the instruments. We shall have occasion to describe the principal instruments when we treat of the applications of Physics to the Arts. But in order to simply understand the general laws which regulate the vibration of air in pipes, we shall confine ourselves here to the consideration of straight pipes in the form of prisms or cylinders, such as exist in organs. Figs. 121 and 122 represent the exterior view and the section or interior view of two pipes of this kind. We can see at the lower part of each of them the pipe through which the air supplied by the bellows is caused to enter: the current first rushes into a box, and thence issues by a chink which is called the mouth of the pipe, and then rushes against the edge of a bevelled plate. A part of the current escapes by the mouth at the exterior of the pipe; the other part penetrates into the interior. This rupture of the current gives rise to a series of condensations and dilatations which are propagated in the column of air. The air of this column enters into vibration and produces a continuous sound, the pitch of which, as we shall see, varies according to certain laws. The mouthpiece which we will describe is that which is called *the flute mouthpiece*. Experiment proves that if we substitute in the same pipes mouthpieces of different forms, it will only modify the quality of the sound without changing its pitch. The pitch does not depend on the substance, wood, ivory, metal, glass, &c. which composes the tube, whence it

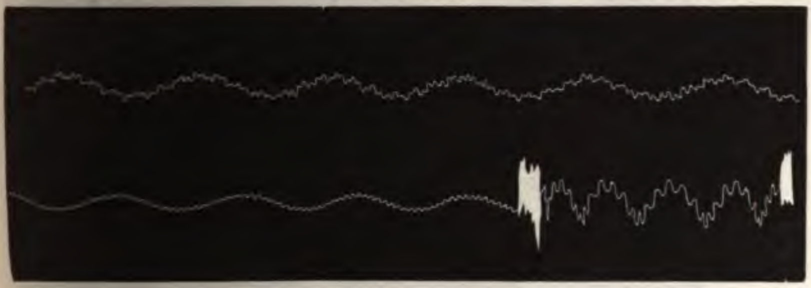

FIG. 120.—Vibrations of compound sounds.

must be concluded that the sound results only from the vibrations of the column of air.

The science of acoustics owes the discovery of the laws which govern the vibrations of sonorous tubes to Father Mersenne and Daniel Bernouilli. We will briefly indicate the most simple of these laws. The first of these *savants* showed that if we compare the sounds produced by two similar pipes of different dimensions—that is, if the one has all its dimensions double, triple, &c. those of the other—then the number of vibrations of the first will be 2, 3 . . . . times less than the vibrations of the other. Thus the smaller of the pipes represented in Fig. 123 will give twice as many vibrations as the other: the sound given out will be the octave of the sound of the largest pipe. This discovery is due to Father Mersenne.

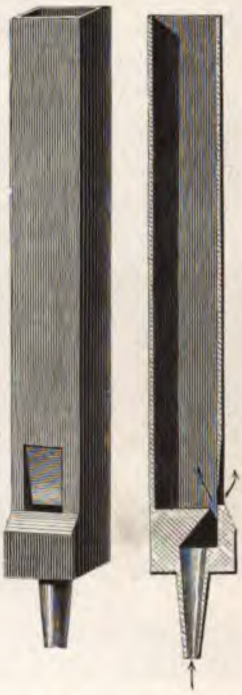

FIG. 121.—Prismatic sonorous pipes.

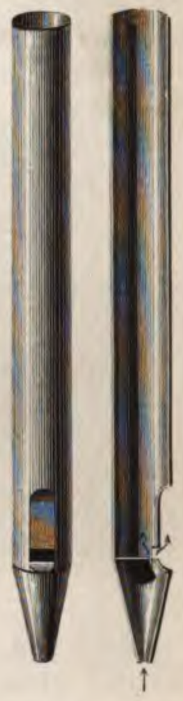

FIG. 122.—Cylindrical sonorous pipes.

Such pipes are sometimes open, and sometimes closed at their upper end. But the law which we are about to mention applies both to open and to closed pipes, provided that their length be great compared to their other dimensions. It must be first observed that each pipe can produce many sounds, more acute or higher as the current of air is greater. The gravest of these sounds is called the fundamental sound; the others are the harmonics; and it is found that, to obtain them, it is sufficient to progressively force in the current of air. And when tubes of different lengths are caused to sound, the longest produce the gravest fundamental sounds, in such a manner that the numbers of vibrations vary precisely inversely as the lengths. For example, whilst the smallest of the four tubes represented in Fig. 124 gives 12 vibrations, the other three give in the same time 6, 4, and 3; or 2, 3, 4 times less; the lengths being, on the contrary, 2, 3, 4 times greater. As I said before, this law is applicable to open as well as closed tubes. But, for the same length, the fundamental sound of a closed tube is different from the sound given by an open one. The vibrations are half the number; or, in other words, the fundamental sound of a closed tube is the same as that of an open tube double the length.

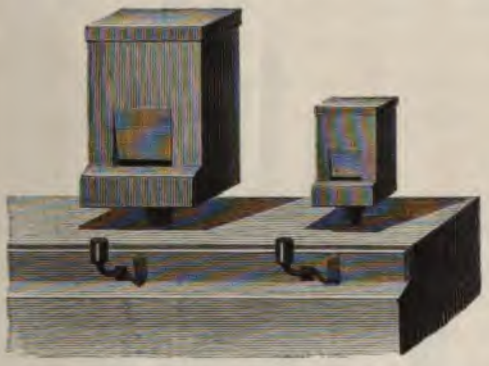

FIG. 123.—Tubes of similar forms.

It only remains for us now to speak of the succession of the harmonic sounds in both of them. Arranging these sounds in order, from the gravest to the most acute, starting from the fundamental note, we find that in open tubes the numbers of vibrations increase according to the series of whole numbers, 1, 2, 3, 4, 5, 6, &c. In closed tubes, these numbers increase according to the series of the odd numbers, 1, 3, 5, 7, &c. From this it results that if we take three tubes, the open one of double the length of the two others, and these, one is open and the other closed, the successive sounds first will be represented by the series of natural numbers—

Long open tube . . 1 2 3 4 5 6 7 8 . . .

and the sounds of the others by

Short open tube . . . 2 . . . 4 . . . 6 . . . 8 . . .
„ closed tube . 1 . . . 3 . . . 5 . . . 7 . . .

that is to say, the sounds of the large tube will be reproduced nately by the two tubes of half the length.

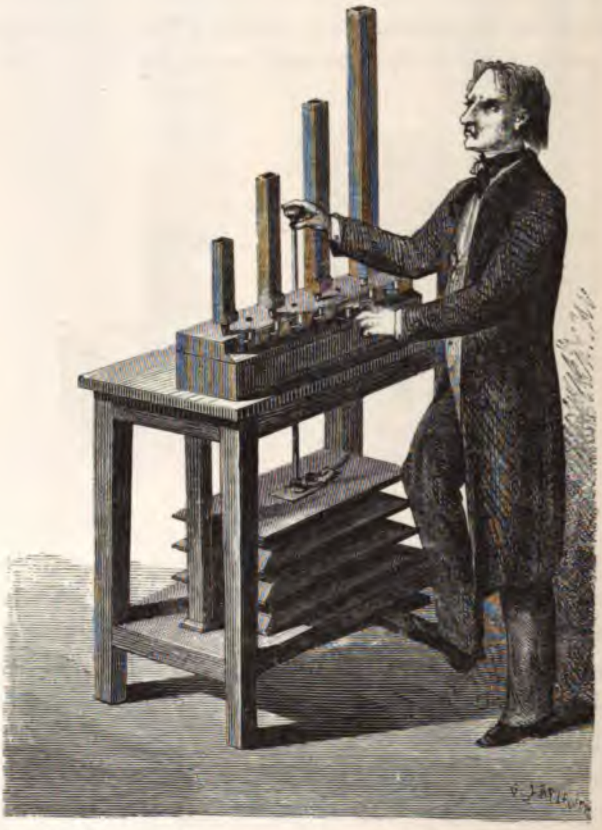

FIG. 124.—Sonorous tubes. Laws of the vibrations of open and closed tubes of different lengths.

We will conclude the study of the phenomena presente sonorous tubes by stating that the columns of air which vibr the interior of them are divided, like vibrating strings, into fixed portions or *nodes*, and vibrating parts or *ventral segments*. The existence of these various divisions is proved in many ways. The most simple consists in lowering into the tube by a string a membrane stretched over a ring, and then to watch the grains of sand with which it is sprinkled. These grains will be agitated under the action of the vibration, when the membrane reaches a ventral segment in any portion of the vibrating column of air. On the other hand, they remain at rest when the position of the membrane coincides with that of a node.

However, theory has completely solved all the problems which relate to this order of phenomena: and the experiments of physicists, always a little less exact than mathematical analysis would require, on account of the complex circumstances under which they are performed, are only verifications of the laws found by analysis. We, who wish especially to describe the curious facts of each part of physics, must confine ourselves to the notions indispensable to the understanding of these facts and their application to industry and the arts.

Sonorous rods are cylindrical rods of wood, metal, glass, or any other elastic substance, which can be caused to vibrate, either by rubbing them longitudinally with a piece of cloth sprinkled with resin, or with a damp flannel. They then give out pure and continuous sounds, the pitch of which for one and the same substance depends on the length of the rod. By the aid of a vice or with the fingers, we grasp the rod, either at one of its extremities or at the middle, or at any intervening part of its length: it is then free at its two ends, or only at one (Fig. 125). Now, if we compare the sound which a rod gives out when fixed at one of its extremities, with that which the same rod or a rod of the same length and substance gives out when fixed at its middle part, we find that the first is graver than the second: the vibrations in the latter are twice as numerous.

If rods of different lengths fixed in the same way are caused to vibrate, experiment shows that the sounds become sharper as the rods are shortened. The numbers of vibrations which constitute their sounds vary in inverse proportion to their length. The vibrations of rods are also governed by the same laws as those of sonorous tubes; and we see that if rods free at both ends are compared with open tubes, the rods fixed at one end correspond to closed ones. Our rod, like the tube, gives out harmonic sounds besides the fundamental note, the ascending series also following the same laws as in the open and closed tubes.

An account of the phenomena which result from sonorous vibrations in bodies of varied forms would be endless. We will confine ourselves to the consideration of those which are produced in plates and membranes. If we cut square, circular, or polygonal plates out of thin wood or homogeneous metal, and fix them solidly to a support at their centre of figure, we obtain very different sounds from them if we draw a bow across their edge and place one or two fingers at certain points of their contours (Fig. 126). Chladni and Savart, whose names are so often to be found in modern researches, and who made sound their special study, made numerous experiments on the vibration of plates of different forms, thicknesses, and surfaces. The phenomenon to which they particularly drew attention was the division of the plates into vibrating and fixed parts. These latter, being nothing else but a continuous series of nodes, were therefore called nodal lines.

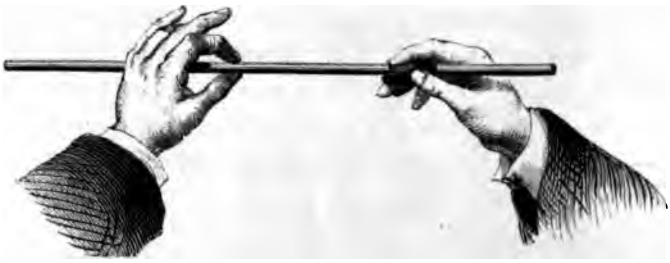
FIG. 125.—Longitudinal vibrations of rods.

To understand and study the positions and forms of these lines, these two learned physicists sprinkled the surface of the plate with dry and fine sand. As soon as the plate entered into vibration, the particles of sand began to move. They deserted the vibrating parts and arranged themselves along the nodal lines, thus producing certain figures or outlines. These lines are often so numerous and complicated, they vary so much for the same plate with the different sounds which this plate gives out, that Savart was obliged to use a particular method to obtain them. Instead of sand, he employed litmus powder, and by means of a damp paper laid on the plate he obtained the impression of each figure. We reproduce here, in Figs. 127 and 128, a series of nodal lines obtained by Savart and Chladni, and we may remark that the figures which contain the most numerous lines correspond to the most acute sounds; in other words, that in proportion as the sound gets higher, the extent of the vibrating parts diminishes.

In square plates, the nodal lines take two principal directions, some parallel to the diagonals, the others parallel to the sides of the plate (Fig. 127). In circular plates (Fig. 128) the nodal lines place themselves either in rays or concentric circles. Bells of glass or metal, and vibrating membranes, are also divided into vibrating parts and nodal lines, as is seen in the experiment of a glass filled with water, represented by Fig. 108. Fig. 129 shows two modes of vibrations of a bell, and the way in which it divides itself into four or six vibrating parts, separated by as many nodes. The first division is obtained by touching the bell in two points distant about a quarter of a circle: the bow is then drawn at about 45 degrees from one of the nodes. The resulting sound is the lowest, and is the fundamental note

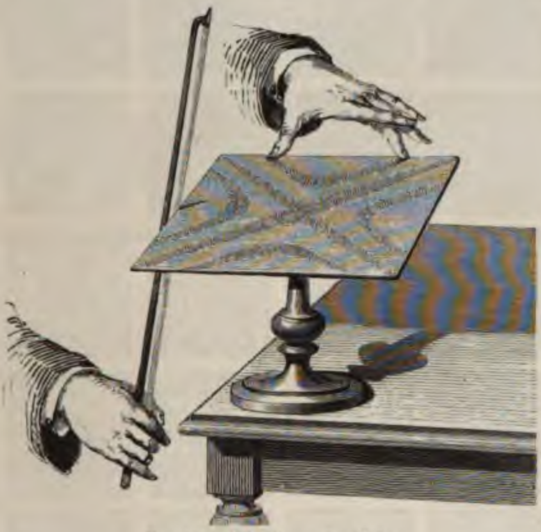

FIG. 126.—Vibrations of a plate.

of the bell. The other division is obtained by placing the bow at a point distant about 90 degrees from the node which is formed by the touch. The bell would be again divided into 8, 10, 12 vibrating parts. It is the same with membranes stretched on frames, which are caused to vibrate by placing near them another sonorous body—for example, a sounding-bell. The vibrations are communicated by the air to the membrane, and the sand with which this is covered indicates the position of the nodal lines.

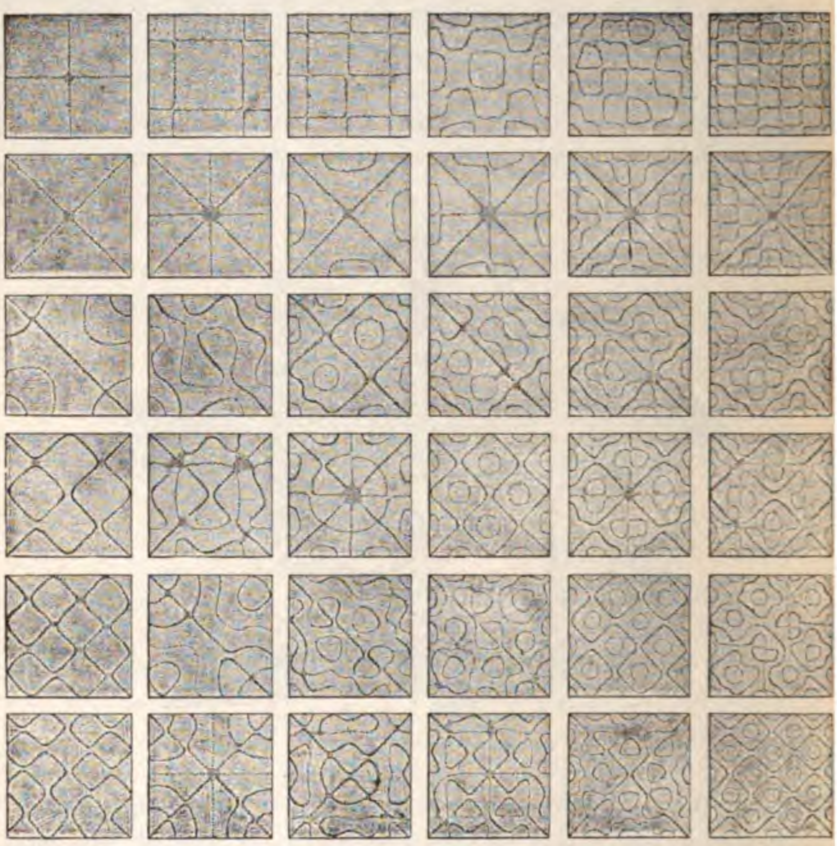

FIG. 127.—Nodal lines of vibrating square plates, according to Savart.

It is well known that when two plates of the same substance and similar figure, but of different thicknesses, give the same nodal lines, the sounds produced vary with the thickness, if the surface is the same; that is to say, that the number of vibrations is proportional to the thicknesses. If the thickness remains constant, the number of vibrations are in the inverse ratio of the surfaces.

We do not yet know the law according to which the sounds produced by the same plate succeed each other when the figures formed by the nodal lines change. We only know that the lowest note produced by a square plate fixed in the centre is obtained when the nodal lines are two in number, parallel to the sides, and pass through the centre as shown in the first plate (Fig. 127). When the two nodal lines form the diagonals of the square (as in the first plate of the second line, Fig. 127), the sound is the fifth of the first one, which may be called the fundamental note.

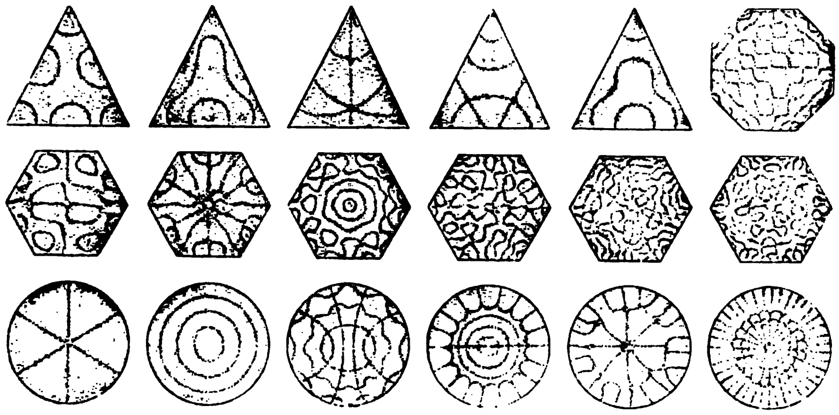

FIG. 128.—Nodal lines of vibrating circular or polygonal plates, according to Ch'adni and Savart.

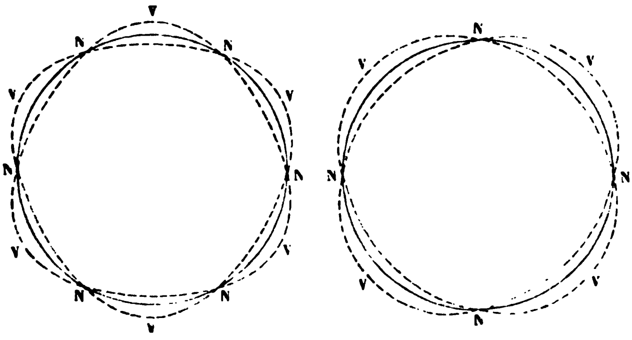

FIG. 129.—Nodes and segments of a vibrating bell.

CHAPTER VI.

PROPAGATION OF SOUND IN AIR.—SOUND WAVES.

Nature of sound waves; their propagation in a tube—The wave of condensation and the wave of rarefaction—Length of sonorous undulations—Propagation through an unlimited medium; spherical waves; diminution of their amplitude with the distance—Direction of sound waves—Co-existence of undulations—Perception of simultaneous sounds; Weber's experiments.

WE have just seen how the vibrations of sonorous bodies can be rendered sensible, and how their number can be counted, and we have proved by experiment the laws of their variations in solids of different forms, and in gaseous, cylindrical, or prismatic columns.

But when a body sounds, the vibrations which its molecules execute, reach our ear, so as to impress us with the sensation of sound only by a gradual disturbance of the mass of air intervening between the centre of disturbance and our organs. In the absence of this vehicle, sound is no longer perceived, or at least only in a very weakened form, after having been propagated through more or less elastic solid bodies, which establish an indirect communication between the sonorous body and the ear. Thus the air itself enters into vibration under the impulse of the movements of the particles of the sonorous bodies, and it undergoes successive condensations and dilatations, which are propagated with a constant velocity, when the density and temperature remain the same, and when the homogeneity of the gaseous mixture is perfect. We will now explain by what means sonorous waves succeed each other in the air or any other gas, and how their length can be measured.

Let us suppose that one prong of a tuning-fork is placed in front of a tube and is caused to vibrate. The vibrations are propagated along the column of air in the tube. We will observe what takes place in the column of air when the prong executes a whole vibration; that is to say, leaves its position *a″* to go to *a′*, and afterwards to return to *a″*, passing each time by its mean position *a* (Fig. 130). This alternating movement is similar to that of the pendulum, so that the velocity of the prong is alternately increasing and decreasing according as it gets nearer to or more distant from the position *a*. During the movement from *a″* to *a′*, the air in the tube, receiving the impulse from the prong, will undergo successive and unequal condensations, which will be transmitted from one to the other, and these waves will be carried along the column of air like the waves along the surface of water. On this point we shall have more to say presently. These condensations at first increasing will attain a maximum; they will then diminish until the vibrating prong has reached the position *a′*. At its return from *a′* to *a″* the same gaseous layers, returned to their normal density, will on the other hand dilate by virtue of their elasticity to fill the space left in the column of air by the second movement of the fork.

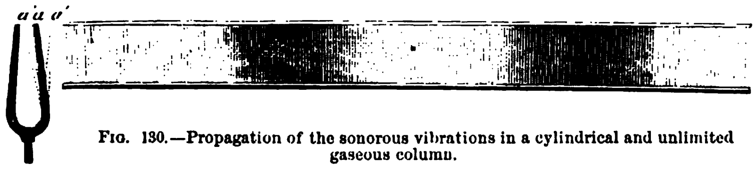

FIG. 130.—Propagation of the sonorous vibrations in a cylindrical and unlimited gaseous column.

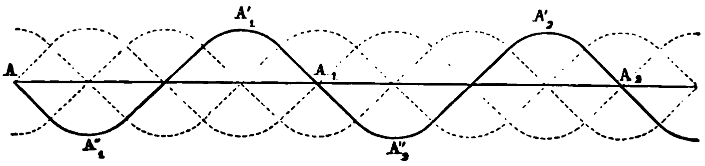

FIG. 131.—Curve representing a sound wave.

To each complete vibration of the prong, a series of condensations therefore corresponds: a condensed half-wave; then a series of dilatations; a dilated half-wave. Their whole forms a complete sonorous wave, which passes along the tube.

To represent to the eye the condition of the column of air in the whole length of a sonorous wave, it has been found convenient to represent the different degrees of condensation by perpendiculars placed above and at right angles to the direction of the wave, and the dilatations which follow (Fig. 131), by perpendiculars traced below this direction: these two lines have a minimum length when the density is the normal density: their maximum lengths correspond to the maximum condensations and dilatations. The curve AA''_1, A'_1, A_1 then represents the state of the successive strata of the tube at the moment when the prong of the tuning-fork has executed an entire vibration; AA_1 is the path traversed during this time,—that is to say, the length of the sonorous wave.

The space traversed by this wave will be double, triple, &c. after the 2, 3, ... first vibrations.

It is now easy to understand how the wave-length of a sound of a given pitch can be calculated. Let us suppose a sound produced by 450 vibrations a second. At the temperature of 15° C.—if such is the temperature of the air at the time of the experiment—as the velocity of propagation is 340 metres during the same interval, it is clear that at the moment when the wave reaches this distance, there are in the air as many successive sound waves as there are complete vibrations from the centre of emission; that is, 450. Each of them has then a length of the four hundred and fiftieth part of the space traversed, that is, of 340 metres; hence the length of wave in this case is 755 millimetres. If we pass now from the case in which the sound is propagated in a column of air to that in which the propagation is made in all directions emanating from a point, the successive condensations and dilatations of the strata of air will be distributed at equal distances from the centre of emanation. The waves will be spherical, without either their velocity of propagation or their length changing. Only the amplitude will diminish, and consequently the intensity of sound, as we have already noticed. Fig. 132 gives an idea of the manner in which sonorous waves are distributed round a centre of emission. We see the series of condensed and dilated half-waves, and the undulating lines starting from the centre show how the condensations and dilatations lose their amplitude in proportion as the distance increases.

To account for the fact that waves are propagated without the particles of air moving with them, sound waves may generally be compared to the movement of a cord which is sharply jerked by the hand. The undulations traverse the cord from one end to the other; and if it is fastened by one of its extremities, the wave returns on itself. In either case, the movement is transmitted without any real change in the distance of the molecules from the point whence the impulse is derived. The same effect is observed when we throw a stone into water; the disturbance produced in the liquid mass is propagated in a series of concentric waves which disappear as the distance increases, but the molecules of water are not transported, as it is easy to prove to oneself by observing the fixed position of light substances floating on the surface. But in these examples, which are otherwise useful in giving us some idea of the mode of propagation of sound waves, there is an essential difference which must not be forgotten. The condensations and dilatations of the air, caused by the vibrations of sonorous bodies, are effected in the same direction as the movement of propagation: they take place parallel to the direction of each

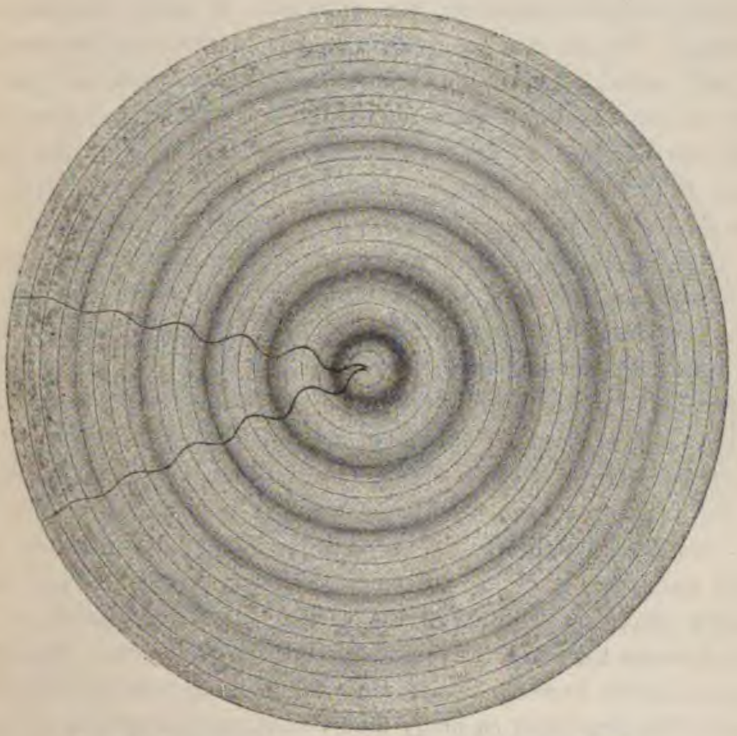

FIG. 132.—Propagation of a sonorous wave through an unlimited medium.

sonorous wave, whilst the undulations of the cord, or that of the surface of the water, are effected in a direction perpendicular to the movement of propagation. We shall see soon that something like this takes place with the waves which traverse the medium called the ether, which have their origin in vibrations from luminous sources.

All this perfectly accounts for the transmission of a single sound which the air carries, so to speak, to our ear. But if the air is thus the vehicle of sonorous vibrations, how does it happen that it propagates, without alteration, the vibrations of many simultaneous sounds? We are at a concert; numerous instruments are simultaneously emitting sounds which differ in intensity, pitch, and quality. The centres of emission are distributed over the room; how is it that the mass of air inclosed by the walls is able at the same time to transmit so many vibrations without the production of complete chaos of sound?

Or again, it is morning. A fine thick rain falls, and the drops on striking the ground produce a multitude of little noises which arrive in a distinct form to our ear; the songs of birds, which the coming of spring awakens everywhere, rise in the air, and seem to pierce the light mist which the rain sheds on the horizon. Above this warbling, cock-crowing, barking of dogs, joltings of a heavy cart on the paved road, the sound of bells, here and there human voices, all of which sing, cry, speak, sounding altogether without the ear finding any confusion. These multiple sounds, the simultaneity of which and their resonances would be discordant if they were all produced in a narrow space, are drowned in the vast extent of the stratum of air which covers the plain, thus mixing into sweet harmony. Here, the same question presents itself: How can the air transmit distinctly and at the same time so many undulations emanating from different centres, so many vibrations which are not isochronous? How can the intensity, pitch, and quality of each sound co-exist, in this elastic and moveable medium, without alteration?

This is a problem the data of which appear so complex, that it is beyond analysis. Nevertheless, theory accounts for these phenomena, the explanation of which appears so difficult at first sight, and simple experiments justify the theoretical conclusions. Two learned geometers of the last century, Daniel Bernouilli and Euler, demonstrated the principle of the co-existence of small movements and oscillations in the same medium. The following is their theory. If we throw into water two or more stones near to each other, we perceive concentric circles produced by each of them, which cross without destroying one another, especially if their amplitude is not too great. Fig. 133, which we borrow from the work of a learned physicist, M. Weber, shows how waves cross each other on the surface of a liquid, and how they are reflected from the sides of the containing vessel. The form of the latter is elliptical, it is filled with mercury, and the waves which are seen on its surface are those produced by the fall of a drop of the liquid in one of the foci of the ellipse. Concentric circular waves are produced at this focus, then reflected waves which all tend to collect at the second focus of the curve. The same results are evidently produced as if a drop had fallen at the same time at each focus.

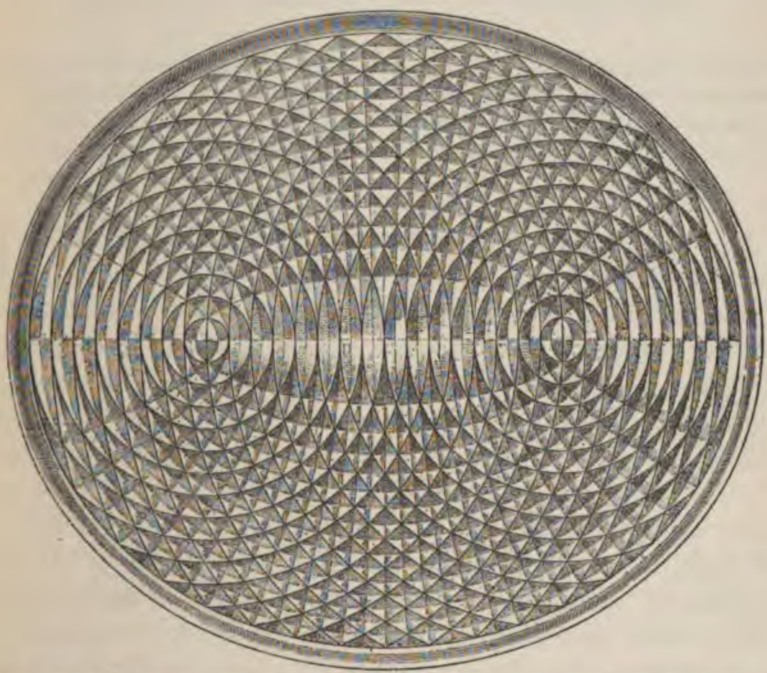

FIG. 133.—Experiment proving the co-existence of waves. Propagation and reflection of liquid waves on the surface of a bath of mercury.

This ingenious experiment proves, then, on the one hand, possible co-existence of waves, and, on the other, the law of reflection. After making the reservation of which we have sp above as to the direction of sound waves, we obtain thus a good idea of the reflection of sounds and their simultaneous pagation through the air.

CHAPTER VII.

MUSICAL SOUNDS.—THE GAMUT, OR MUSICAL SCALE.

Distinction between noises and musical sounds—Definition of the gamut ; intervals which compose it—The scale of the musical gamut is unlimited ; convention which limits it in practice— Names and values of the intervals of the natural major scale—Modulations ; constitution of the major gamuts proceeding by sharps and flats – Minor scale.

THE human ear, as we have remarked in the preceding chapter, is limited as regards its perception of sound. It has been proved by experiment that 32 simple vibrations per second is the limit of grave sounds, while that of acute sound is 73,000 vibrations. Between these extreme limits the scale of sounds is evidently continuous, so that there is an infinity of sounds having a different pitch appreciable to the ear, and passing from the grave to the acute, or from the acute to the grave, by imperceptible degrees.

All the sounds comprised in this scale, and susceptible consequently of being compared among themselves as regards pitch, are what are called *musical sounds;* by combining them by means of succession or simultaneity, according to determined rules of time, pitch, intensity, or quality, the musician is able to produce the effects which constitute a musical composition.

Are all the sounds and noises perceptible to the ear, musical sounds ? Undoubtedly not, if we mean by musical sound that which a composer or artist thinks right to introduce into his work to add to the desired effect. Not only must these sounds be closely connected by bonds which are determined by the pitch, but they must also unite certain particular qualities the examination of which belongs to the domain of art rather than of science. The question becomes altered if the term musical sound is applied exclusively to those whose pitch is appreciable, and which the ear can compare to other higher or graver sounds, the vibrations of which may be measured according to a constant and regular law. In this case, physicists distinguish noises properly so called from musical sounds. Noise frequently proceeds from a confused mixture of different sounds which the ear can scarcely distinguish from each other, but the separation of which is possible. At other times, noise is nothing but a sound the vibrations of which do not last long enough to enable the hearer to appreciate the relative pitch. The cracking of a whip, the collision of two stones or two pieces of wood against each other, and generally of any two bodies which are but weakly sonorous, the report of fire-arms, are noises of this last kind; whilst the dull surging of a stormy sea and the rustling of leaves in a forest proceed from the mixture of a multitude of sounds or confused noises.

The attempts which have been made to compare the pitch of simple noises with musical sounds prove that the distinction of which we speak is more apparent than real. Physicists have succeeded, by varying the dimensions of a series of wooden balls and causing them to come together in collision, in making them emit the tones of the musical gamut; but, in order that the ear should easily seize their relationship, it is necessary that the sounds succeed each other at very short intervals. On the other hand, we can separate the noises formed of sounds mixed together, and can distinguish some of the elementary sounds of which these noises are composed. The sensibility of the ear, joined to the habit of comparisons of this kind, contributes greatly to render these distinctions possible.

Let us now endeavour to form some idea of the succession and connection of sounds which constitute musical scales known under the name of gamuts and which form the physical basis of modern music.

The name of "gamut" is given to a series of seven sounds which succeed each other, proceeding from the grave to the acute or from the acute to the grave, and which are comprised between two extreme notes having the following character, viz. that the highest sound is produced by double the number of vibrations of the lowest. The most acute note being the eighth of the series, the two extreme notes are the octaves of each other: one being the lower octave, the other the higher one. If we now start from the eighth note, considered as the starting-point of a series similar to the first, and if we take care to compose this new series of notes having between them the same degrees of pitch as the first, it will be noticed that the impression left on the ear by their succession has the greatest analogy with that which results from hearing the notes of the first scale. A melody formed of a succession of notes taken from the first series, preserves the same character if it is sung or played with the help of notes of the same order taken in the second series. It would be the same if we formed in a similar manner one or more gamuts higher or lower than those of which we have just spoken.

A musical scale of this kind, formed of consecutive gamuts, is unlimited, or at least has no other limits than those of our power of perceiving sounds.

Before giving the *intervals* which separate the successive notes of the gamut, or in other words the ratio of the number of vibrations which correspond to each of them, we may remark that the note from which we start to form a gamut, or to *study* music, is arbitrary, as there are an infinite number of similar musical scales placed by nature at the disposal of musicians. But, for the *practice* of music, the want has been felt of taking conventionally a fixed point of departure. Hence in modern music we find certain definite notes (the vibrations of which are determined by the vibrations necessary to produce one of them) called by certain definite names: the names being the letters of the alphabet, A, B, C, D, E, F, G, repeated for each octave. So long as it is merely a question of singing or of music executed by the human voice, a convention of this kind is not necessary, as the voice is an organ sufficiently flexible to emit at will notes of any degree of acuteness or gravity within its natural limits. Hence for such purposes we may consider the gamut as a thing independent of any particular pitch, and it is convenient to call the notes of such a gamut by some other names. Those used are derived from the first syllable of each line of a Latin hymn written by Paulus Diaconus:—

Ut quam laxis
*Re*sonare fibris
*Mi*ra gestorum
*Fa*muli tuorum
*Sol*vi polluti
*La*bii reatum
*S*ancte Johannes.

The Italians substituted *Do* for *Ut* for the first note of the gamut, in the seventeenth century.

Our arbitrary names for the seven notes of this gamut, which may be independent of pitch, in passing from the gravest to the highest note, are as follows:—

1st note.	2d.	3d.	4th.	5th.	6th.	7th.
Do,	Re,	Mi,	Fa,	Sol,	La,	Si.

After what we have said of the manner in which the preceding gamut is formed, and of the analogy, if not the identity, which exists between the notes in different octaves, we can understand why the same names have been given to the notes of the successive gamuts. Musicians distinguish them by placing numerical signs after the names of the notes, to mark the order of succession of the gamut. The two scales we now give—one lower, the other higher than the former one—may for our purposes be written thus:—

Gamut above	Do_{-1}	Re_{-1}	Mi_{-1}	Fa_{-1}	Sol_{-1}	La_{-1}	Si_{-1}
Gamut below	Do_{2}	Re_{2}	Mi_{2}	Fa_{2}	Sol_{2}	La_{2}	Si_{2}

It also results from the constitution of the successive scales that the notes of the same name are an octave from each other, like the extreme notes of each scale. Thus, Do_{-1}, Re_{-1}, Mi_{-1}, are the acute octaves of Do_2, Re_2, Mi_2. Before proceeding further, let us recall the laws of the vibrations of strings and tubes, and we shall understand that if we stretch a series of seven strings, so as to make them give out the seven notes of the scale, we shall obtain the seven notes of the acute scale, the octave of the first, by dividing the strings into two equal parts. If instead of strings we had taken seven open or closed tubes, giving the scales by their fundamental notes, we must take seven tubes of half the length to obtain the more acute scale, and seven tubes of double the length to obtain the notes of the lower scale. If we compare each of the seven notes of a scale to the lowest note—to that which forms what is called the tonic, or key-note, in reference to their pitch there are many different intervals, of which the names are as follows:

From	Do	to	Do	*Unison.*
	Re	to	Do	*Second.*
	Mi	to	Do	*Third.*
	Fa	to	Do	*Fourth.*
	Sol	to	Do	*Fifth.*
	La	to	Do	*Sixth.*
	Si	to	Do	*Seventh.*
And lastly,	Do_{-1}	to	Do	*Octave.*

The musical interval is defined in physics as the relationship of the numbers of vibrations of the notes of which it is formed. Unison and the octave are the only ones of which we have given the value: 1 or $\frac{1}{1}$ measures the interval of unison; 2 or $\frac{2}{1}$ measures the octave. It only remains for us to speak now of the numbers which measure the other intervals. The following are the numbers as they are now adopted by the majority of physicists:—

Do — Do Unison = 1
Re — „ Second = $\frac{9}{8}$
Mi — „ Third = $\frac{5}{4}$
Fa — „ Fourth = $\frac{4}{3}$
Sol — „ Fifth = $\frac{3}{2}$
La — „ Sixth = $\frac{5}{3}$
Si — „ Seventh = $\frac{15}{8}$
Do — „ Octave = 2

As these only express the relationship, they can be written in the form of whole numbers, and the seven notes of the scale will then be found to be represented in one or the other of the following ways:—

Do	Re	Mi	Fa	Sol	La	Si	Do
1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2
24	27	30	32	36	40	45	48

In other words, if the tonic or key-note, Do, be produced by 24 vibrations in a given time, the following notes will be produced by 27, 30, ... 48, &c.

It is easy to calculate by the aid of this table the consecutive interval of the notes of the scale.

$$\text{Do}\underbrace{\qquad\quad}_{\frac{9}{8}}\text{Re}\underbrace{\qquad\quad}_{\frac{10}{9}}\text{Mi}\underbrace{\quad}_{\frac{16}{15}}\text{Fa}\underbrace{\qquad\quad}_{\frac{9}{8}}\text{Sol}\underbrace{\qquad\quad}_{\frac{10}{9}}\text{La}\underbrace{\qquad\quad}_{\frac{9}{8}}\text{Si}\underbrace{\quad}_{\frac{16}{15}}\text{Do}$$

It will be seen that these intervals are not equal. The greatest, although unequal, are called major seconds or tones, and the smallest minor seconds or semi-tones. Although the major seconds are not equal, it is agreed to place them under the same denomination, and the scale is composed of the following successive intervals:—

A major second = tone.
A major second = tone.
A minor second = semitone.
A major second = tone.
A major second = tone.
A major second = tone.
A minor second = semitone.

A scale thus formed is called a major scale, to distinguish it from the scale formed of intervals succeeding each other in another order which is called a minor scale.

The musical scale thus formed is not sufficient for the composer in the case of melodies, for if confined to such narrow limits they would have a monotonous character incompatible with the variety of impression he might wish to produce. To increase his resources, he passes, in the same piece, from one scale to another; and it is to these transitions, the rules of which form so large a part of the art of music, that the name of *modulations* has been given. The new scales into which modulation takes place differ only from the tonic scale in the position of the new key-note; the order of succession and the relationship of pitch of the new scale remain the same. Let us write the succession of two consecutive gamuts, from one octave to another:—

Do Re Mi Fa Sol La Si Do Re Mi Fa Sol La Si Do

We can readily comprehend that by a simple substitution of the two intervals which separate the Mi from the Sol,—that is to say, by causing Mi to be followed by a major second so as to precede the Sol by a minor second, a fresh scale will be produced presenting the same series of intervals as the first, but commencing by the note Sol instead of by Do: as follows:—

Scale of *Do Major.*

Do Re Mi Fa Sol La Si Do Re Mi Fa Sol La Si Do

Scale of *Sol Major.*

Do Re Mi Fa Sol La Si Do

This may be written in ordinary musical fashion:

C D E F G A B C D E F G A B C

G A B C D E ♯F G

Hence by adding the sign ♯ to Fa in the first scale, which means that we lengthen the interval below it and reduce the interval to the next note to a higher semitone, we have the two former octaves written in the

Scale of *Sol Major.*

Do Re Mi Fa♯Sol La Si Do Re Mi Fa♯Sol La Si Do

Indeed it is seen that the two first intervals of this new scale are two major seconds, Sol-La, La-Si, and that they are followed by a minor second, Si-Do; then follow three major seconds, Do-Re, Re-Mi, and Mi-

Fa♯, so that at last the scale is terminated by a minor second, Fa♯-Sol. The new note must receive an entirely new name; it is distinguished from the Fa which it replaces by the name of Fa sharp: the Fa natural is said to have been *sharpened.* But it is clear that we need not regard these difficulties. We have only to consider the note Sol as a new Do, and proceed as before modulation.

We can not only sharpen notes, as we have seen, but we can flatten them; this process is indicated by the sign ♭.

The following is the complete table of the major scales obtained by this means:—

Scale of "Do" Natural Major.

	Sharps.		Flats.
Scale of Sol	1	Scale of Fa	1
Re	2	Si♭	2
La	3	Mi♭	3
Mi	4	La♭	4
Si	5	Re♭	5
Fa	6	Sol♭	6
Do♯	7	Do♭	7

The series of notes sharpened successively is as follows:—Fa, Do, Sol, Re, La, Mi, Si. The series of the flattened notes is precisely inverse:—Si, Mi, La, Re, Sol, Do, Fa. The important point to remember is that these arrangements only alter the place of the start-point; the natural scale, when once the start-point is determined, is invariable. As the complete exposition of the rules which serve to form these musical scales would be beyond the range of this work, we will restrict ourselves to saying that musicians also use minor scales, presenting the peculiarity that the order of the ascending intervals differs from that of the descending intervals.

Minor Scale.

Ascending intervals.	Descending intervals.
La	La$_2$
. . . major second.	. . . major second.
Si	Sol♮
. . . minor second.	. . . major second.
Do	La♮
. . . major second.	. . . minor second.
Re	Mi
. . . major second.	. . . major second.
Mi	Re
. . . major second.	. . . major second.
Fa♯	Do
. . . major second.	. . . minor second.
Sol♯	Si
. . . minor second.	. . . major second.
La$_2$	La

In this minor scale, we see that the two notes, Fa♯ and Sol♯ of the ascending scale are replaced by the two notes Fa, Sol, in the descending one: musicians indicate this by using the symbol of each of these two notes, the sign ♮, which they call a *natural*, and which shows the return of the two sharpened notes to their primitive or natural state. The same sign also indicates a change of the same kind in a note already flattened.

CHAPTER VIII.

OPTICAL STUDY OF SOUNDS.

Vibrations of a tuning-fork; the sinuous curve by which they are represented—Appreciation of the comparative pitch of two notes by the optical method of M. Lissajous—Optical curves of the different intervals of the scale; differences of phase—Determination of the concord of two tuning-forks—Vibrations of columns of air in tubes; manometric flames, M. Koenig's method—Comparative study of the sounds given out by two tubes; the nodes and neutral segments of columns of air.

WE have described several different methods for counting the number of vibrations executed by a sonorous body at the moment when it gives out a certain sound: the toothed wheel syren and vibroscope or phonautograph, are the instruments used for this purpose. In the last, the vibrations themselves are inscribed on a surface, and their amplitude and number can be easily shown: this is the graphic method of the study of sound. M. Lissajous, a French physicist, has during the last few years studied the vibratory movements of sonorous bodies by the aid of the eye, and thus substituted the organ of sight in place of the ear for distinguishing the relationship of sounds; from this cause the method of examination is called the *optical method.* The following is a brief description of it. By its means even a deaf man might be trusted with researches on the relative pitch of sound. "There is no one among us," said M. Lissajous in a lecture explaining this new method, "who has not, in his childhood, at the risk of setting fire to the paternal house, plunged a stick into the fire, in order to afterwards move the glowing end with rapidity through the air, to watch with the natural curiosity of youth the brilliant lines of fire produced as by a magic brush, which appeared, then vanished in an instant from the sight. This is the experiment which forms the basis of the optical method."

A tuning-fork is a little instrument formed of a double metall rod, the united branches of which, like a long horseshoe, are su ported by a cylindrical column resting on a stand (Fig. 134). I inserting a piece of wood larger than the space between the tw extremities of the prongs, and rapidly withdrawing it, the elast prongs of steel are caused to vibrate, and their oscillations pr duce a musical note, the pitch of which depends on the form a dimensions of the instrument; physicists sometimes produce vibr tions by drawing a bow across the prongs. The tuning-fork is used regulate the tone of instruments or voices in orchestras and theatre the normal tuning-fork is that which produces a certain defini number of vibrations for the note C.

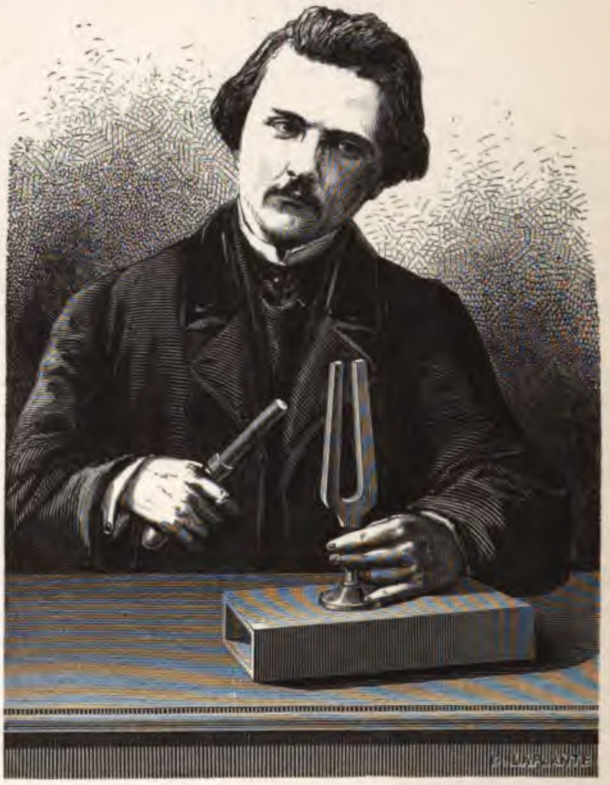

FIG. 134.—A tuning-fork mounted on a sounding-box.

To render the vibrations of a tuning-fork visible, M. Lissajous fixes by its convex surface, a small metallic mirror at the extremity of one of the prongs, while the other prong has a counterpoise to render the vibratory movement regular.

"If we look in this mirror," he says, "at the images reflected from a light a few yards distant, and then cause the tuning-fork to vibrate, we observe that the image lengthens itself in the direction of the length of the prongs. If the tuning-fork is then turned round on its axis, the appearance changes, and we see in the mirror a bright sinuous line, by the form of the undulations of which the greater or less amplitude of the vibratory movement is indicated."

By using a second mirror, which reflects the image to a screen after having passed through a convergent lens, the phenomenon can be made visible to a large audience. In this case a brighter source of light must be employed—that of the sun or the electric light, for example—and the second mirror must be turned round a vertical axis to obtain the transformation of the rectilinear image into a sinuous curve.

Hitherto we have spoken solely of rendering visible the vibrations of a single sonorous body. M. Lissajous has succeeded in distinguishing the comparative pitch of two notes and measuring the relationship of the numbers of vibrations which correspond to each of them. Two tuning-forks are taken, both fitted with mirrors (Fig. 135)—but whilst the axis of one is vertical, that of the other is horizontal—in such a way as to have the two mirrors opposite to each other. A ray of light issuing from a small orifice is thrown upon one of these mirrors: it suffers reflection, strikes the mirror of the second tuning-fork, and is again sent back to a fixed mirror. A third reflection projects the luminous ray on a white screen, where a clear and bright image of the opening is visible so long as the two tuning-forks remain at rest.

If we now cause the vertical fork to vibrate, we immediately perceive that, instead of a point of light, the vibratory movement produces a luminous line, elongated in the vertical direction. If, while the vertical tuning-fork is at rest, the horizontal one is caused to vibrate, the image is elongated in a horizontal direction. Lastly, if both forks are caused to vibrate simultaneously, the image which now results from two movements, one at right angles to the other, will describe a luminous curve on the screen, and the form of this curve will depend on the relationship which exists between the duration of the two systems of vibrations, the amplitude of the oscillations, and lastly the time which separates the beginnings of two consecutive vibrations executed by both forks: and it is this time which is called the difference of phase.

M. Lissajous has in this manner determined the luminous curves given by forks tuned so as to produce the intervals of the scale, as it is adopted by physicists.

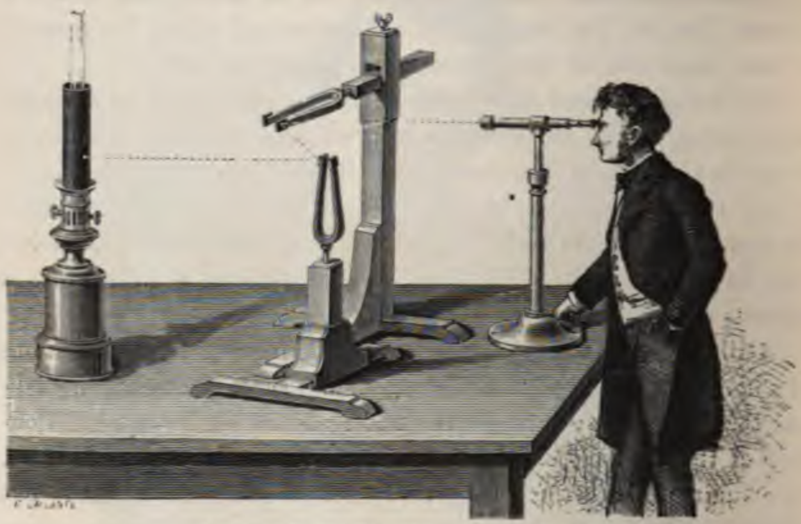

FIG. 135.—Optical study of vibratory movements.

If the two tuning-forks are in unison, the relationship of the number of vibrations is 1; in other words, the vibrations effected in equal times are of equal number. The difference of phase is itself nothing; the vibrations begin at the same time in both tuning-forks: there is a luminous oblique right line, the diagonal of a rectangle, the sides of which have a length which varies with the amplitude of the simultaneous vibrations. This right line is changed into an ellipse or oval, when there is difference of phase. Fig. 136 shows the curves given by differences of phase equal to $\frac{1}{8}$, $\frac{1}{4}$, $\frac{3}{8}$, and $\frac{1}{2}$. They are again produced, but in an opposite direction, if the differences are $\frac{5}{8}$, $\frac{3}{4}$, $\frac{7}{8}$, and 1.

When two forks are an octave apart they give a series of curves represented in Fig. 137, which indicate that one of the forks executes a vibration in a horizontal direction, whilst the other makes two in a vertical direction.

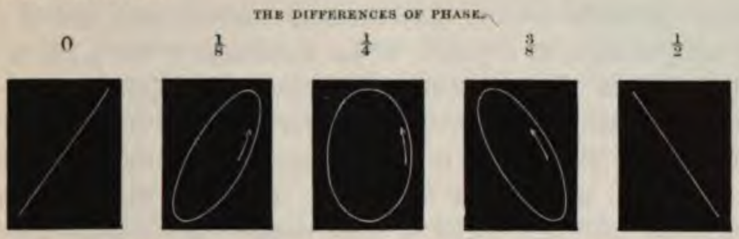

FIG. 136.—Optical curves representing the rectangular vibrations of two tuning-forks in unison.

If the numbers of vibrations are in the ratio of 3 : 2, 4 : 3, 5 : 4, 5 : 3, 9 : 8, and 15 : 8, the forks are tuned to intervals of fifth, fourth, third, sixth, major second, and seventh. In Fig. 137 the optical curves obtained in the case of the fourth and fifth, with the variations of form which proceed from the differences of phase, are shown. By studying these curves it is possible to count the number of vibrations made by the luminous point in a horizontal and a vertical direction; and as they are all effected in the same time, we also

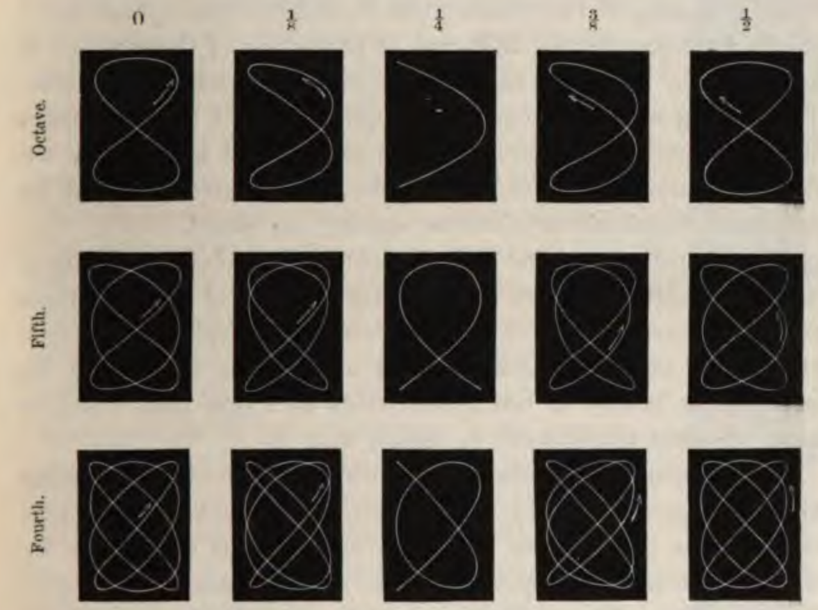

FIG. 137.—Optical curves. The octave, fourth, and fifth.

learn the relative numerical relation of the two notes. When the pitch of the forks agrees, the same curve continues on the screen during the whole time of their simultaneous resonance, and it ends by being reduced to a point. If, on the contrary, the pitch is not quite the same; if, for instance, the octave is not quite perfect, the effect is the same as if there had been a continual changing in the difference of phase, and the curve passes imperceptibly through all the forms indicated in the figure. The time that it takes to accomplish the entire round of these transformations being noted, it is concluded that there is a difference of one vibration on the lowest tuning-fork, and two vibrations on the highest, relatively to the number which the true octave would produce.

This method is so precise that the slightest difference is detected. Thus, let us suppose two tuning-forks in unison. The optical curve will be according to the difference of phase, one of those which is represented by Fig. 136, and it will remain during all the vibrations. If one prong of the tuning-fork is slightly warmed, it will cause a decrease of pitch: the unison will be altered, and immediately we observe a variation in the form of the optical curve produced on the screen, which shows that the concord has ceased.

The optical method not only determines the relative numbers of vibrations, but also shows the absolute number of the vibrations which correspond to a given sound. Having once made a tuning-fork which gives the normal concert pitch of the note C, adopted by orchestras, it is easy to use it afterwards as a type from which to construct other tuning-forks in unison with it.

M. Lissajous has applied his method to the study of vibrating strings, and even to that of sound propagated through air. In order to effect this, he illumines the string at one of its extremities, by casting a luminous ray upon it: in the second instance he receives the movements of the air on a membrane to the surface of which a small bright bead is affixed.

We have forgotten to mention that if, in all these experiments, the curves traced by the luminous points are visible at the same time in all their parts—that is to say, if an entire revolution is terminated before the persistence of the impression of light on the retina had ceased—as the duration of this persistence is about a tenth of a second, we may infer that such is, at the maximum, the time employed by the image of the point to traverse the entire sinuosity of the curve.

Such is the original method employed by M. Lissajous to render vibratory movements, and the most delicate peculiarities of these movements, perceptible to the eye. It will be seen, therefore, that we were right in saying that a person deprived of the faculty of hearing would be able to compare sounds with greater precision than the most susceptible ear could do by hearing alone.

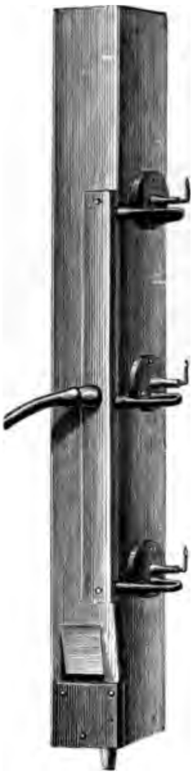
FIG. 138.—Open tube with manometric flame.

During the last few years a musician, M. Koenig, has invented another very ingenious method of studying the vibrations of columns of air in tubes, which we will now endeavour to describe. One of the walls of a sonorous tube is perforated by a certain number of openings—with three, for example, corresponding to the node of the fundamental note and to the two nodes of its octave; each of these openings is closed by a small chamber from which issues a gas jet communicating with a tube which conveys the coal gas to the chamber and jet. That part of the chamber which communicates with the interior of the sonorous tube in contact with the vibrating gaseous column is formed of a thin sheet of caoutchouc, and is slightly extended by the pressure of the gas. It is then eminently elastic, and yields to the least increase of pressure. Let us suppose the gas jet to be lighted: if the interior pressure of air of the tube increases, the caoutchouc membrane is compressed, so that the capacity of the small chamber diminishes and the flame is elongated; it shortens, however, if the pressure diminishes, because the interior capacity of the chamber then increases. It will be seen, therefore, that the gas light is in reality a manometer, an indicator of changes of pressure; and M. Koenig calls the flames which issue from the gas jets at the side of the pipe *manometric flames*. Let us imagine that the sonorous tube is fitted to a pair of bellows, and that the air enclosed by it is thrown into vibration. We know that when a gaseous column vibrates, it is alternately condensed and dilated by the propagation of sonorous waves. If the sound produced by the tube is the fundamental note, the node is formed at the middle of the gaseous column: at this point the dilatation and compression of the air attain their maximum. The successive condensations and dilatations are then transmitted to the manometric chamber of the middle portion of the tube, the flame of which elongates and shortens itself alternately, executing a series of movements which indicate the vibratory condition of the sonorous body. If we cause the tube to give the octave of the fundamental note, there will be a segment opposite to the middle chamber and a node at each of the others. We shall then observe that the end flames are very much agitated, whilst the middle flame will remain immoveable.

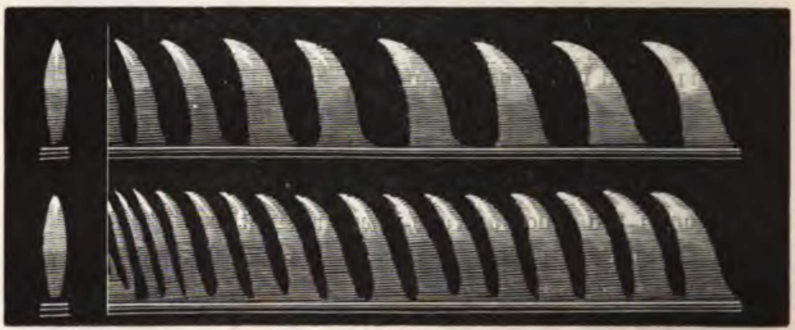

FIG. 139.—Manometric flames. Fundamental note, and the octave above the fundamental note.

We know that in sonorous tubes the vibrating column of air is divided into separate parts by the nodes, the middle points of which are vibrating segments. At the nodes the air is at rest, but its density is alternately at a maximum and minimum. On the other hand, each vibrating segment is the point where the disturbance is at its greatest, whilst the density of the air remains invariable. Now, as the variation of density determines the variations of pressure, and as these are transmitted to the flames by the membranes of the chamber, it follows that the manometric flames are very much agitated when they are opposite the nodes, whilst they remain at rest if they correspond to a segment of the vibrating column. M. Koenig's method enables us to prove the existence of these different points: by reducing the flames to a small size, the agitation which they undergo opposite the nodes puts them out, whilst they remain alight opposite the segments. To make the elongations and shortenings of the flame more sensible, M. Koenig uses a mode of projection similar to that which M. Lissajous has adopted for the optical method. He places a mirror near the jet of gas, and causes it to rotate by means of toothed wheels and a handle.

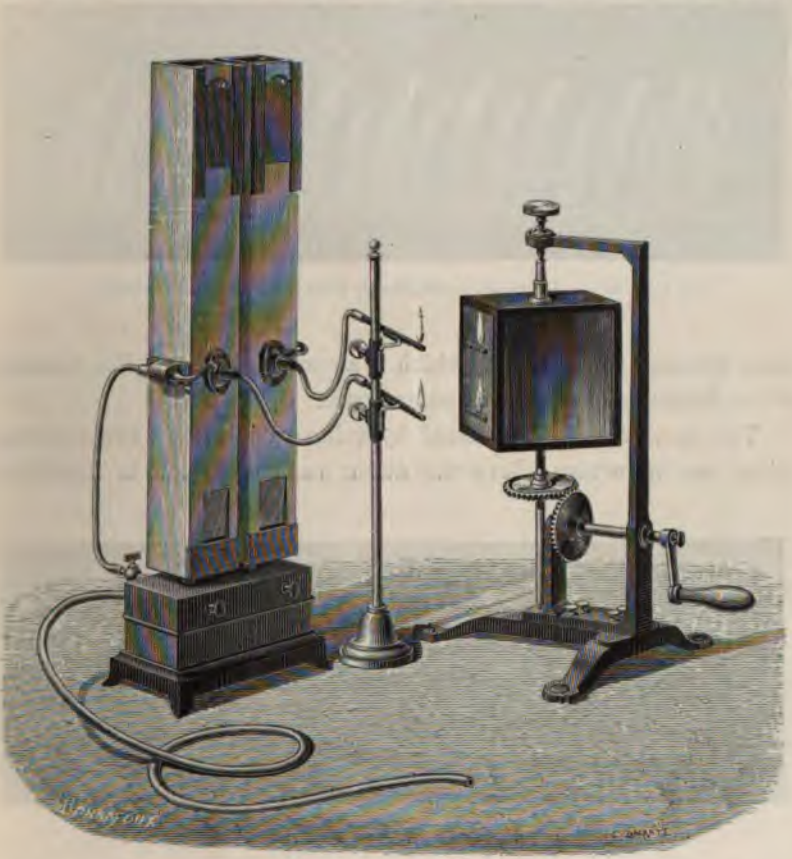

FIG. 140.—Apparatus for the comparison of the vibratory movements of two sonorous tubes.

When the tube sounds, the revolving mirror shows a succession of flames separated by dark intervals, or a luminous band with a toothed edge. By placing a converging lens between the jet and the revolving mirror, a clear and bright image is projected on the screen, where all the peculiarities of the phenomenon can be studied.

Thus, in the two experiments which we have just described, where the tube gives successively the fundamental note and its octave, the change of light shows itself immediately in the manometric flames, as shown by Fig. 139, where the upper series represents the effect produced by the vibration of the fundamental note, whilst the lower series proceeds from the note which is an octave higher. The number of the flames is double in the second case.

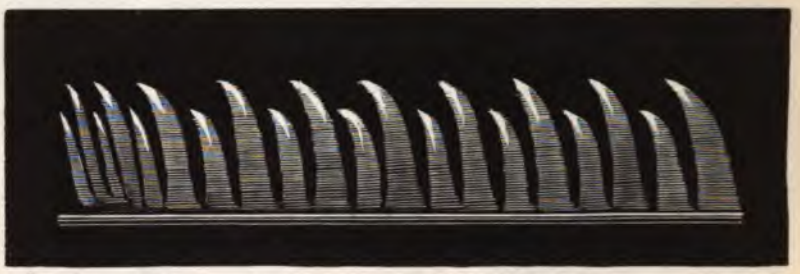

FIG. 141.—Manometric flames simultaneously given by two tubes at the octave.

The same result is obtained by fixing to a bellows two different tubes, one an octave above the other, each of which is furnished with a manometric chamber; when the flames are reflected on the same revolving mirror, they give the two series which are represented above (Fig. 141). To compare the pitch of the notes of tubes of different intervals, M. Koenig employs another method. He causes the gas, the combustion of which produces the flames employed, to pass from one chamber to another, but only one jet is lighted. By causing the two tubes to sound simultaneously, the same flame is

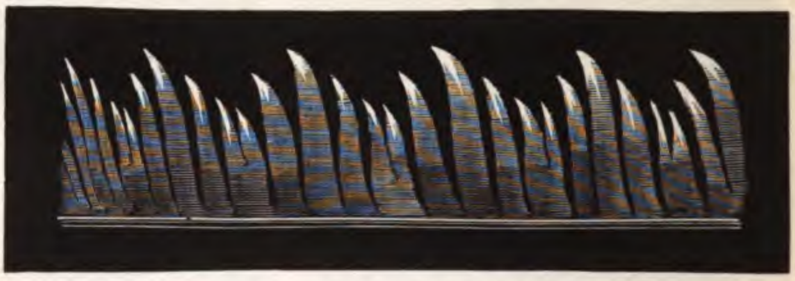

FIG. 142.—Manometric flames of two tubes of a third.

agitated by the two systems of sonorous waves, and following each other we see on the screen flames alternately larger and smaller, the number of which depends on the musical interval of the notes. "This disposition," says M. Koenig, "is even preferable to the first, whenever the relation between the two tubes is not perfectly simple." For example, for tubes giving C and E (a third) the observation of four images corresponding to five becomes difficult; but the succession of images which, by groups of five, are elongated and shortened, and which are seen in the revolving mirror by the second arrangement (Fig. 142), is not of a very complicated appearance.

CHAPTER IX.

QUALITY OF MUSICAL NOTES.

Simple and compound notes—Co-existence of harmonics with the fundamental notes—The quality (clang-tint) of a note depends on the number of the harmonics and their relative intensity; M. Helmholtz's theory—Harmonic resonant chambers (*résonnateurs*); experimental study of the quality of musical notes—Quality of vowels.

WE have seen that among the qualities of a musical note there is one which distinguishes notes having the same pitch and intensity. The A of a violin has not the same character as the A of the flute or piano, or that of the human voice; and further, on the same instrument a note does not sound the same if the mode of producing it changes. Thus the note obtained by a violin string vibrating its whole length is not identical with the same note obtained from another string by the stopping with the finger. Human voices can also be distinguished from each other, as we can prove at any moment, although the notes may be of the same intensity and pitch.

This particular quality of notes is called the quality, clang-tint, or *timbre*.

For a long time very vague ideas prevailed as to the cause of this singular modification of sound, and the hypotheses proposed by several mathematicians—among them Euler—could never be verified by experiments. In the present day, thanks to the labours of a contemporary German philosopher, M. Helmholtz, this obscure part of the science of acoustics has been fully explained: and the cause of the quality of sound has been discovered. Some very ingenious instruments constructed by M. Koenig have considerably simplified the experimental verification.

When a string, tube, rod, or any sonorous body produces a note, we have, besides the fundamental note, the pitch of which can be easily distinguished by the ear, more feeble notes, which correspond to vibrations of less amplitude and variable velocities, effected by different parts of the sonorous body. The co-existence of these vibrations produces a compound note: on the one hand the most intense fundamental note; and on the other, harmonic sounds whose numbers of vibrations are multiples of the number of vibrations of the fundamental note.

According to M. Helmholtz, the clang-tint of a note depends at once on the number of harmonic notes which accompany it, and on the relative intensity of each of them. The exactitude of this explanation has been proved by the following means:—

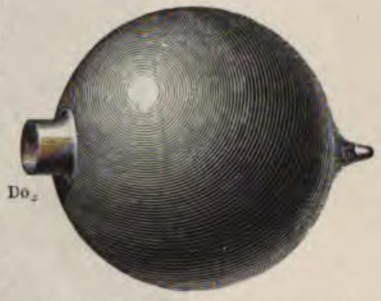

FIG. 143.—M. Helmholtz's resonance globe.

A series of hollow copper globes, of different sizes, pierced with two openings of unequal diameter, were constructed in such a manner that in each of them the interior mass of air resounds when a body giving a certain note is placed before the large opening (Fig. 143). These are called *resonance globes*, and their property consists in strengthening the notes for which they are tuned, and by which the air which they enclose is thrown into vibration. This being established, M. Koenig constructed an apparatus formed of eight globes tuned to the series of the harmonic sounds, 1, 2, 3, 4, 5, 6, &c.: for example, for the notes do_2, do_3, sol_3, do_4, mi_4, sol_4, &c. Fig. 144 shows them fixed on a stand one below the other; they each communicate by an india-rubber tube placed over the small opening with a manometric chamber; the gas jets of these chambers are placed parallel to the revolving mirror, and we can easily see on the surface of this mirror, by the agitation or repose of these flames, which of the globes has entered into vibration. When a sonorous body, a tuning-fork for instance, is caused to vibrate, and is moved before the openings of the globes, the note is strengthened as soon as it passes before that which gives out the note of the same pitch; and the flame of this globe appears agitated in the mirror. If then, a compound tone is produced, to study the harmonics of this note and their relative intensity, the sonorous body must be moved before the openings of the globe, and certain flames will be seen agitated whilst the others remain at rest. As the agitation is more or less rapid, the intensity can be calculated.

By this means we can show that a variation in the clang-tint of a note of certain pitch results from the difference of the harmonics which compose it, and from the predominance of one or other of its secondary tones.

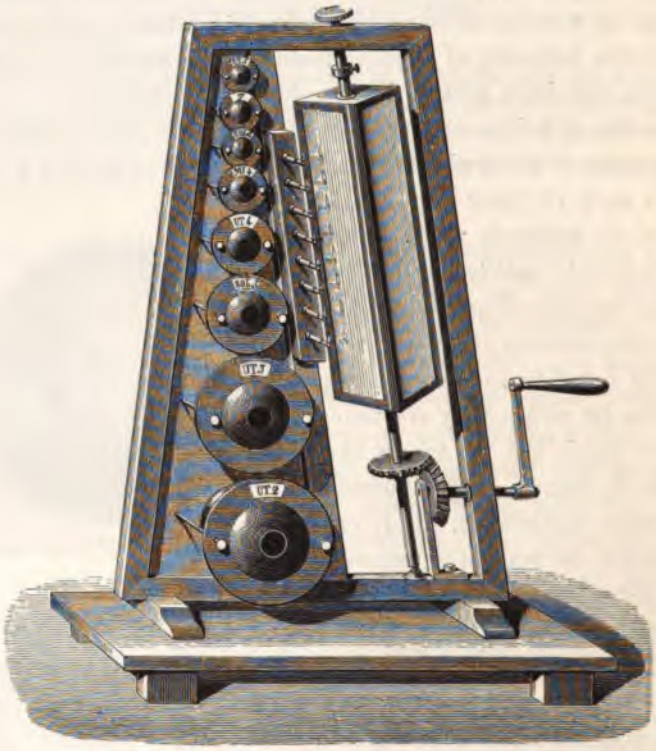

FIG. 144.—M. Koenig's apparatus for analysing clang-tints.

M. Helmholtz, by applying this method to the study of the clang-tints of vowels, has discovered that the vowel *A*, for example, is produced by a compound of certain harmonics; so that when the larynx emits this particular sound, the mouth is in such a position as to give the predominance to such of the harmonic notes as are required.

The harmonics vary for each vowel sound, and are produced by the cavity of the mouth, &c., being so arranged as to resound most strongly to the harmonic required. Thus in the case of the vowel-sound *O*, we require the fundamental and a strong higher octave; *A* requires the third; *E* an intense fourth; while in *U* the harmonics are thrown into the shade.[1]

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[1] This interesting subject is treated at some length in Professor Tyndall's work on "Sound," to which we refer for further particulars.

CHAPTER X.

HEARING AND THE VOICE.

Organ of hearing in man; anatomical description of the ear—The external ear; the orifice and auditory meatus—The intermediate ear; the drum and its membrane; chain of small bones—The internal ear or labyrinth; semicircular canals, the cochlea and fibres of Corti; auditory nerve—Rôle of these different organs in hearing; the difference between hearing and listening—The organ of the voice in man; larynx, vocal cords—Clang-tint of voices.

ALL physical phenomena are revealed to man by the impressions which they produce on his organs. To him they are simple or compound sensations, according as one or several senses conduce to their production. Thus it is by the help of the organ of sight that we see light; by touch that we perceive the sensation of heat; the efforts our muscles make to lift a heavy body, the sight of a falling stone, reveal to us the existence of gravity; and the ear gives us the sensation of sound.

But to study the phenomena in themselves, and to discover the conditions and the laws of their production, it is necessary for us to distinguish in the sensations experienced, what belongs to our organs, and what is a stranger and external to them: by this means only the real nature of the phenomena becomes intelligible to us. In truth, this abstraction is never complete, because there cannot be one observation or one experiment which does not require the presence of man and the intervention of one or other of his senses to prove the results. How shall we, then, succeed in abstracting ourselves, so to speak, in the study of physical phenomena? It is by varying in all possible ways their modes of production, as well as the methods which we use to observe them; in a word, it is by the mutual control of the sensations, one over the other, that the truth can by degrees be brought to light, and the phenomena appear to us in their individuality and independence. Thanks to the use of these methods, we now know the nature of sound; we know that it consists of a peculiar movement of the molecules of elastic, solid, liquid, or gaseous elastic bodies. We have already proved the existence of sonorous vibrations and studied their laws. It now remains for us to know how these vibrations are communicated to our organs, until the time when they form, so to speak, an integral part of our being, when the disturbance which they communicate to our nerves is transformed into a particular sensation, which is the sensation of sound. The ear is the special apparatus, in man and all animals, designed to collect sonorous vibrations and to transmit them to the auditory nerve. Let us endeavour to explain, according to the anatomists, the disposition and the *rôle* of the different parts of this organ.

Every one knows the external ear, situated on each side of the head, and composed of two parts,—the *ala*, or wing, and the auditory canal.

The *ala* or wing of the external ear (*concha*), A (Fig. 145), consists of a cartilaginous membrane, its form varying with different persons, but most often it is of an irregular oval shape, becoming smaller at its lower part. At the centre there is a sort of funnel, the *trumpet*, which forms the entrance of the auditory meatus, B, a kind of tube or sonorous pipe which terminates at a certain point where the intermediate ear begins: there, separated from the auditory canal by a very thin and delicate membrane, C—the tympanic membrane—is the tympanum, a sort of drum (D), known as the drum of the ear. The membrane of the tympanum is inclined very obliquely to the axis of the auditory nerve, so that its surface is much greater than the cross section of the canal at the point of its insertion. The drum of the ear is pierced with four openings, two of which are through the wall which faces the membrane, and as one is of a circular and the other of an elliptical form, they are designated the round and the oval window; the latter the *fenestra ovalis* of our anatomists. At the lower part of the tympanum enters by the third opening a canal, I, which makes communication between the middle ear and the outer air through the intervention of the nasal fosses. Lastly, a fourth opening is in the upper part of the drum. In the interior of the tympanum there is a series of little bones known as the *chain of small bones*, or *auditory ossicles*. Fig. 146 represents the forms and relative positions of these. One, the hammer (*malleus*), M, rests on one side on the membrane of the tympanum, and the other on the anvil, E (*incus*). The two others are the lenticular bone, L (*os orbiculare*), and the stirrup (*stapes*), K, both named on account of their form. The bottom of the stirrup is joined to the membrane which is tightly stretched over the *fenestra ovalis*. Two little muscles help to move the hammer and the stirrup, to support them with more or less force against the adjoining membranes, and to prevent too violent motion.

Behind the drum of the tympanum is the internal ear, which appears to be the most essential part of the organ of hearing. It is protected by the hardest parts of the temporal bone which anatomists call the petrous bone. Three separate cavities compose the internal ear: they are, the vestibule, at the middle; the semicircular canals, G, at the upper part; and the cochlea, H, at the lower part. The whole forms the labyrinth, the interior of which is covered with a membrane which bathes in a gelatinous liquid, the *perilymph*. Into this liquid plunge the ramifications of the auditory nerve, which penetrates to the labyrinth by a bony canal called the inner auditory meatus.

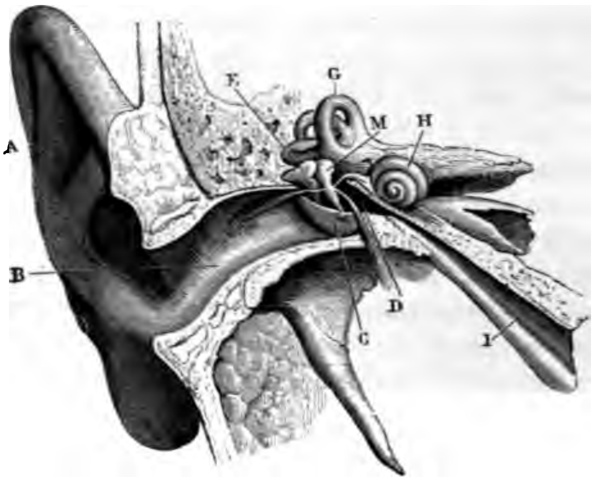

FIG. 145.—The human ear; section of the interior tympanum; chain of small bones. Internal ear; labyrinth.

Such is a description of the principal parts which constitute the organ of hearing in man: as we descend the animal series, the external and middle ears gradually disappear, but in proportion as the organ is simplified the remaining parts are more developed. It now only remains for us to explain the use of each of them.

Evidently the object of the external ear is to collect and reflect sonorous waves into the opening of the external auditory canal. This is proved by the fact that animals which have the wing of the ear moveable turn this opening towards the place whence the sound comes, as soon as their attention is awakened. Man has not this faculty; but it has been observed that the most delicate ears belong to those whose ear-wing is furthest from the skull; and we all know that to be able to hear better, it suffices to enlarge the surface artificially with the hollow of the hand. The external auditory canal transmits the sonorous vibrations, after strengthening them, to the membrane of the tympanum, then by the chain of small bones to the inner ear.[1] The Eustachian tube, by bringing the outer air into the box of the tympanum, maintains on both sides of the membrane the same pressure.

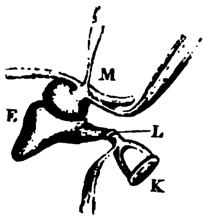

FIG. 146.—Details of the auditory ossicles.

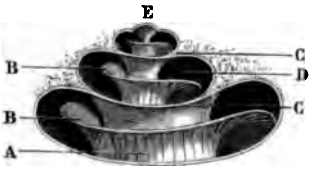

FIG. 147.—Section of the cochlea.

As to the small bones, besides their function of transmitting vibrations to the inner ear more easily and energetically than a gaseous body would do, it appears certain that they transmit the motions from the tympanic membrane to the *fenestra ovalis*, and perhaps that they stretch the membrane of the tympanum and that of the *fenestra ovalis*, and thus render them more susceptible to vibratory movement. Hence the difference which exists, as regards sensations between the modes of audition which are characterized by the

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[1] The solid parts of the head and the teeth directly transmit sonorous vibrations to the internal ear. If we suspend a bell to a string between the teeth, and stop the ears, a deep sound is transmitted by the thread, the teeth, and petrous bones to the internal ear. Deaf people whose infirmity is only owing to a bad conformation of the internal organs, can hear in this way.

[illegible]

[illegible]

From the preceding remarks we see that the theory of hearing still presents some [illegible] is rather the task of physiologists than of physicians [illegible]

[illegible] admirable in this organization of one of [illegible] the conservation of the individual [illegible] his [illegible] the outer world and which is the [illegible] and profound enjoyments, is its wonderful faculty to hear an indefinite multitude of sounds. The co-existence of vibrations in the air and in media suitable for the propagation of sound accounts for this property of the ear, which transmits to the nerves and thence to the brain the thousand modifications of the elastic medium among which we live.

Let us conclude this study of the phenomena of sound by a short description of the organ of the voice in man, of this natural musical instrument by the aid of which we communicate our ideas in their most delicate and intimate shades, an instrument so flexible and complete that the most perfect artificial instrument cannot succeed in the diversity of shades and qualities which enables the human voice to express the most varied sentiments and passions.

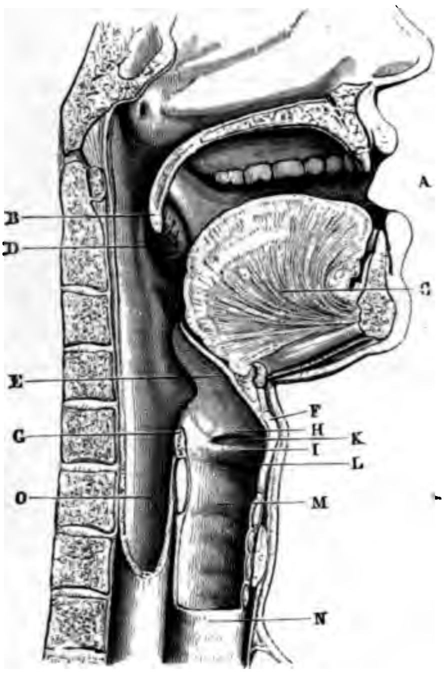

FIG. 149.—The human voice; interior view of the larynx. Glottis; vocal chords.

The vocal organ is nothing more than a wind instrument; that is, the sounds are produced by more or less rapid vibrations of the air, in its passage through an opening of particular form more or less restricted. The air passes from the lungs by a tube or annular canal, N, called the windpipe; from that it penetrates into the larynx, M, where it enters into vibration and produces the notes of the voice, then into the pharynx, a funnel which enters the back of the mouth. The sound then arrives in the cavities of the nasal fosses and of the mouth, which acts as a resonant chamber and gives a special clang-tint to the note.

Figure 149 shows the interior conformation of the larynx. It is as it were a kind of cartilaginous box, the base of which terminates in the windpipe, N, and the summit by the hyoid bone, formed like a horse-shoe. The epiglottis, E, is a sort of moveable valve, which by descending can close the larynx at its upper part, thus preventing food from penetrating into it, which would produce extinction of the voice, and suffocation. Underneath the epiglottis is the glottis, K, an opening comprised between two systems of folds leaving a cavity between them called the ventricles of the larynx. These folds bounding the glottis are the so-called "vocal chords," or ligaments: these are elastic cushions, with broad bases and sharp, free, parallel edges; they are stretched to a degree of tightness which enables them to vibrate quickly so as to produce audible sounds, the vibration being set up by the passage of the air. When quiescent, the glottis is V-shaped, and air can pass without producing sound.

Physiological experiments have shown that the vocal chords vibrate like the serrated mouths of sonorous tubes, and that sounds thus produced are more or less acute according as the tension, more or less strong, of the vocal chords modifies the form and dimensions of the opening between them called the glottis. When the note arrives in the mouth, its pitch is determined; it is not submitted to any other modifications than those which constitute the clang-tint, or which form the articulated voice. The movements of the pharynx, tongue, and lips serve to produce these various changes, which we have not the space to speak of here. We will only state that men's voices, differing from those of women or children by their depth, owe their character to the greater dimensions of the larynx and the opening of the glottis. The rapid development of this organ in young people, towards the age of puberty, is the cause of the transformation which we observe in their voices.

BOOK III.

LIGHT.

BOOK III.

LIGHT.

WE are about to enter a fairy-like, enchanted world, a world of wonders, where rubies, sapphires, topazes, and all kinds of precious stones send forth their fires; where every object is of incomparable beauty and splendour; in a word, into the world of light and colour.

Thus, the cycle of the phenomena of nature gradually passes in review before us. After having studied the physical forces, more particularly in their mechanical action, this action being so general and so constant that it appears to give us more the idea of matter, we have now to notice a series of phenomena more variable and more directly connected with the movements of organized beings, the principle of which is a condition of life—the phenomena of light and heat.

It is difficult if not impossible to have a clear idea of the nature of the phenomena of light on the surface of the various celestial bodies which people space. But, on the earth, what variety and magnificence we witness during the day and the night! If the eye of man cannot look at the dazzling star when it shines in all its brilliancy in a cloudless sky—if even the portion of the sky surrounding the solar disc hurts the sight—the whole country, on the other hand, is resplendent, and sends us back the rays which inundate it. Moreover, thanks to this double journey of the rays of light, from the sun to the terrestrial objects and from them to us, a wonderful transformation is effected. The source of all this emits but one tone, one colour, while a multitude of shades and various colours are sent back to us by the objects seen. This metamorphosis is so familiar that we do not even suspect it: each body appears to us to possess in itself a colour of its own, and the presence of a luminous source, whatever it may be, at first appears to have no other influence than to render it perceptible.

The variable nature of atmospheric conditions also adds to the beauty of the spectacle by the continual changes which it brings to the thousand shades of light and colour. During the night the spectacle is different: it is a softer light which slowly succeeds the diurnal illumination: but the charm thus becomes even more grateful. The light of the moon at its different phases, the millions of stellar fires which sprinkle the dark azure of the starry vault, the misty veil with which the landscape is enveloped, multiply, with the glimmer of twilight and the aurora, the various beauties of the scene. Light and colours! . . . . For the artist there is such a powerful magic in these words, that often, being smitten with passion for them alone, he sees nought else, and considers them as alone the objects of art. But he has no need to visit museums to enjoy these beautiful things: the Rembrandts, Lorrains, and Veronese have drawn their inspiration from the country. Rich jewel-cases do not help us to admire the wonders of light. He who knows how to observe can, without even changing his place, see them displayed around him: a ray of sunlight which penetrates into his room and passes through a glass of water, the morning or evening horizon, dewdrops which shine suspended like diamonds or pearls on the leaves of trees, the rainbow colours of a liquid bubble, and a thousand other phenomena which are continually following and modifying each other,—surely this is an inexhaustible source of pictures for an artist, a subject full of studies for the *savant!*

Light gives us all this: day and night, dazzling illumination and feeble glimmers which traverse the profound darkness, decided colours and innumerable shades, oppositions and transitions, similitudes and contrasts, and always harmony. Is it then astonishing that primitive races, in their simple ignorance, reserved their adorations, through admiration and gratitude, for the source whence came both light and heat? This was in their minds the beneficent and fruitful sovereign, the true God of the universe. Modern science, less respectful but more intelligent, placed face to face with physical agents, has tried to solve the secrets of the phenomena of light, and has succeeded, with the help of a delicate and profound analysis, in discovering the principal laws. The result of these beautiful researches will now be the object of our exposition.

Let us first consider the principal sources of light.

CHAPTER I.

SOURCES OF LIGHT ON THE SURFACE OF THE EARTH.

Sources of cosmical light : the sun, planets, and stars—Terrestrial, natural, and artificial luminous sources—Lightning ; Polar auroræ ; electric light ; volcanic fires ; light obtained by combustion.

LIGHT sources may be divided into two classes, according to their origin: the first, the cosmical, are exterior to the earth; the second exist on our planet or in its atmospheric envelope. The Sun must be placed first among the cosmical sources of light. It is the most powerful source of all to us. The mean brightness of its light is, according to Wollaston, 800,000 times greater than that of the full moon; and as the brightest star in the sky, Sirius, does not give much more than the 7,000th part of the Moon light, it follows that it would require at least five thousand six hundred millions of similar stars to illuminate the earth to an equal extent to that of the Sun. It is well known that the movements of rotation and translation of our planet are of such a nature that the light of the Sun is periodically distributed over each part of its surface. The light is variable according to the season and hour of the day, the greater or less elevation of the solar disc above the horizon having much to do with its apparent luminous intensity; but the interposition of the vaporous masses which constitute clouds, mists, and fogs, tends also considerably to enfeeble it.

The solar light reaches us some time after the Sun has sunk below the horizon. The upper strata of the air remain directly illuminated when the Sun has ceased to light up the place of observation and the lower strata; and this is the cause of twilight, the length of which is prolonged by a phenomenon which we shall soon study under the name of "refraction of light."

Among those lights which are of celestial origin, there are some which are not direct luminous sources: the Moon, for example, which makes our nights so bright, receives her light from the Sun before reflecting it to us. This is also the case with planets and their satellites.

The sources of light which have their origin on our planet may be divided into natural and artificial lights. Lightning in storms, fire produced by volcanic eruption, polar auroræ, so frequent in northern and southern regions, together with shooting stars and bolides, and perhaps the zodiacal light, must be ranked with the first. We may also add those lights which are developed in certain organized beings, the phosphorescence of certain insects, the marine infusoria known as the *Noctilucæ*, some being vegetable and some mineral.

We all know that light can be procured artificially by combustion, which is nothing more than chemical combination accompanied by the disengagement of light and heat. Electricity is also a source of light; and science, as we shall presently learn, has succeeded in utilizing its powerful light, the intensity of which is so great that it can only be compared to the dazzling brightness of the Sun itself.

CHAPTER II.

THE PROPAGATION OF LIGHT IN HOMOGENEOUS MEDIA.

Light is propagated *in vacuo*—Transparent, solid, liquid, and gaseous bodies; transparency of the air—Translucid bodies—Light is propagated in a right line in homogeneous media; rays, luminous pencils, and bundles of rays—Cone of shadow, broad shadow, cone of penumbra—The camera obscura—Light is not propagated instantaneously—Measure of the velocity of light by the eclipse of Jupiter's satellites—Methods of MM. Fizeau and Foucault.

LIGHT is propagated either *in vacuo*, or within certain solid, liquid, or gaseous media. When we speak of *vacuo*, we mean, with philosophers not an absolute vacuum, but a space entirely deprived of all tangible substance, as the interplanetary space probably is, or the space above the mercury in a barometer, and vessels exhausted by an air-pump. The light which reaches us from the Sun and stars, and that which passes through the exhausted receiver of our laboratory, prove that light, unlike sound, does not require a ponderable medium for its propagation. As regards the passage of light through the air and different gases, through water and a great many other liquids, and lastly, through solids like glass, special experiments are not required to prove this.

We also know that luminous bodies are not the only ones which produce in us the sensation of light; but they serve to light others and to render them visible. Bodies thus illuminated then become secondary luminous sources, whence light emanates, to be propagated, through the media of which we have just spoken, as direct light. Bodies may, then, be arranged, as regards their property to emit, receive, or allow light to pass through them, into different classes: viz., as self-luminous bodies, non-luminous transparent, and non-luminous opaque bodies.

[illegible] Light which passes
[illegible] always partly absorbed;
[illegible] greater in proportion to
[illegible] the light. Objects
[illegible] a shallow layer of
[illegible] increases, the clearness
[illegible] appeared to be inter-
[illegible] a deeper tint,
[illegible] is seen but the
[illegible] sea off the coast
[illegible] of a beautiful
[illegible] disappear at a
[illegible] At first the disc
[illegible] darkened in
[illegible] the colour,
[illegible] not be dis-
[illegible] yellow or mud
[illegible] depths of from
[illegible]

[illegible] it is pure,
[illegible] that of Mont
[illegible] objects
[illegible] portion of
[illegible] Mont Blanc
[illegible] the air
[illegible] but
[illegible] haze, and
[illegible] metres
[illegible] would
[illegible] range of
[illegible] who
[illegible] with the
[illegible] horizon.
[illegible] are some
[illegible] glass, with-
[illegible] distinguished
[illegible] liquids,
[illegible] with a

thin layer of oil, its translucency is increased, and may even be changed into transparency if the paper is sufficiently thin.

Even substances which are believed to be absolutely opaque allow a certain quantity of light to pass through them when they are cut into very thin plates. Stones, wood, metal, and many other substances are opaque. Nevertheless, if we place between the eye and a luminous source a sheet of gold leaf, for instance—gold-beaters obtain it so thin that 10,000 put together have not the thickness of a millimetre—we see a beautiful green colour, which proves the transmission of light, not through holes produced during the beating, but through the very substance of the metal itself. The extreme smallness of the objects of which microscopists examine the internal structure—infusoria, microphytes, &c.—doubtless explains their transparency.

When the light emitted by a luminous source or an illuminated body reaches the eye, it can only do so by passing through diaphanous or translucent media. Let us inquire what is the course of its propagation, and what effect is produced if it meets in its path with bodies of greater or less opacity? Such are the simplest problems of which philosophers have demanded a solution by experiment in studying the phenomena which are manifested under these circumstances.

The most simple case is that in which light traverses a perfectly transparent homogeneous medium; that is, having the same density and composition throughout, and reaches the eye in a direct manner. Experiment proves that it is propagated in a right line. Between the flame of a candle and the eye, let us interpose a series of opaque screens, each pierced with a little hole: in order to see the light, it is obvious that the holes of all the screens must be in a straight line. Daylight cannot be seen through a long tube if this tube is not rectilinear, or at least if its curvature is too much to allow a straight line to pass through it without touching the sides. Shut yourself in a perfectly close and dark room, and admit the light of the sun by a little hole made in the shutter. Almost immediately you will see a luminous cone which marks the passage of the light through the air, and you will easily prove that the outlines of this cone are perfectly rectilinear. In this case, it is not the air itself that we see, but the particles of dust suspended in the air made visible by illumination on the dark ground of the room.

The propagation of light in a straight line can also be proved when

[illegible]

[illegible]

more or less luminous, which visibly proceed in a right line. But we shall presently see that as the atmosphere is composed of strata of

Fig. [illegible].—Rectilinear propagation of light.

variable densities, the light which successively passes through these strata no longer moves in a right line. On the surface even of the earth, in order that this movement be exactly in a straight line, the transparent medium must be perfectly homogeneous, whether this medium be air, or gas, water, glass, &c.

Let us now explain what philosophers mean by the terms ray, beam, and pencil of rays.

Light emanates or radiates from luminous bodies in every direction; and is propagated in a right line, as we have just seen, in homogeneous media. A luminous ray is a series of points, regarded simultaneously or successively, of which one of the lines followed by the light is composed; a pencil is a collection of small rays starting from the same source, and a beam or bundle of rays is the union of many parallel rays. Luminous pencils are cones having their summits at the source of light. But when the luminous source is very distant, as in the case of the sun and stars, the rays coming from the same point of the source have such a slight divergence that they may be considered parallel, and we have a beam.

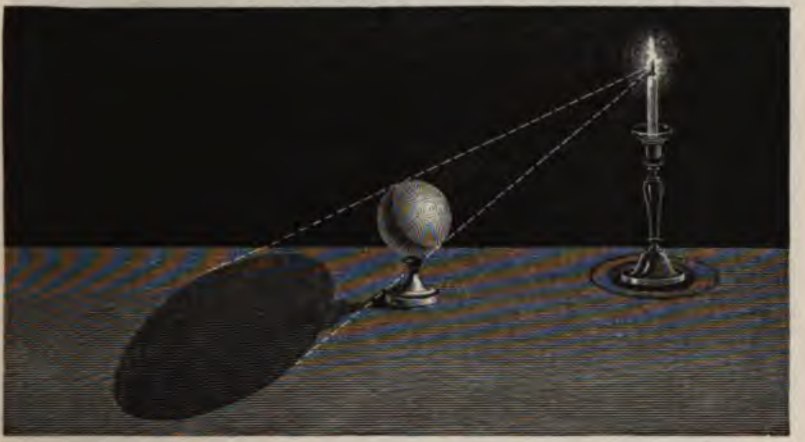

FIG. 152.—Cone of shadow of an opaque body. Completed shadow

If there were in nature nothing but self-luminous bodies and media of absolute transparency, we should only see the first. Not only is the transparency of the various media imperfect, but a multitude of bodies interfere with the passage of light, scatter it in all directions, and become illuminated or, in other words, visible. From this result half-tones and shadows.

When an opaque spherical body is in the presence of a luminous *point* and at a certain distance from it, one part of the body, that towards the light, is illuminated, the other does not receive light. It is in shadow. Moreover those portions of space situated beyond the dark surface of the body receive no light, as we can easily prove by placing a screen behind the body and observing the shadow thrown on the screen. The luminous point is, in this case, the summit of a cone tangent to the outlines of the opaque body, a luminous cone in its fore part and dark in its prolongation, which is called the cone of shadow. In this case, which is never perfectly realized, the portion of the opaque body not illuminated is totally invisible (Fig. 152), and the separating line of the shadow and the light is exactly marked.

When the source of light is a luminous body of finite dimensions, the case is otherwise. Fig. 153 clearly shows that the surface of a body lighted up is divided into three parts: one of which is lighted up at the same time by the whole of the luminous surface; another which receives no light; and a third, intermediate between the others, which receives only a fraction of the total light, and which constitutes what is called the penumbra. The space situated behind the opaque body, opposite the luminous source, is likewise divided into an absolute cone of shadow, and a cone enveloping the first which is the cone of the penumbra. Beyond this double cone, the space is entirely illuminated. If the luminous body is greater than the opaque one, the cone of shadow is limited; it is cylindrical, if the two bodies are equal; and

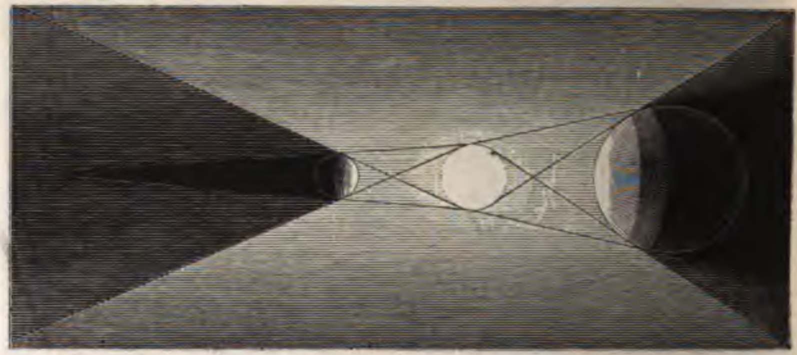

FIG. 153.—Cones of umbra and penumbra.

lastly, we see a divergent cone if the opaque body is larger than the illuminating one (Fig. 153).

The penumbra gives to the outlines of illuminated round bodies that half-tint which renders the contrast between lights and shades less decided and softer. As the cone of the penumbra continues to widen more and more, it follows that the full shadows cast by an illuminated opaque body are paler and less clear, as its distance from the screen is greater, as every one can prove for himself. The perforated cards which are given as playthings to children are an application of the effect of the half-light produced by penumbræ. When the card is very near the wall or screen on which the shadow is thrown, this shadow is well defined, and the effect which the artist desired to produce is not obtained; at a proper distance, the penumbra, spread out

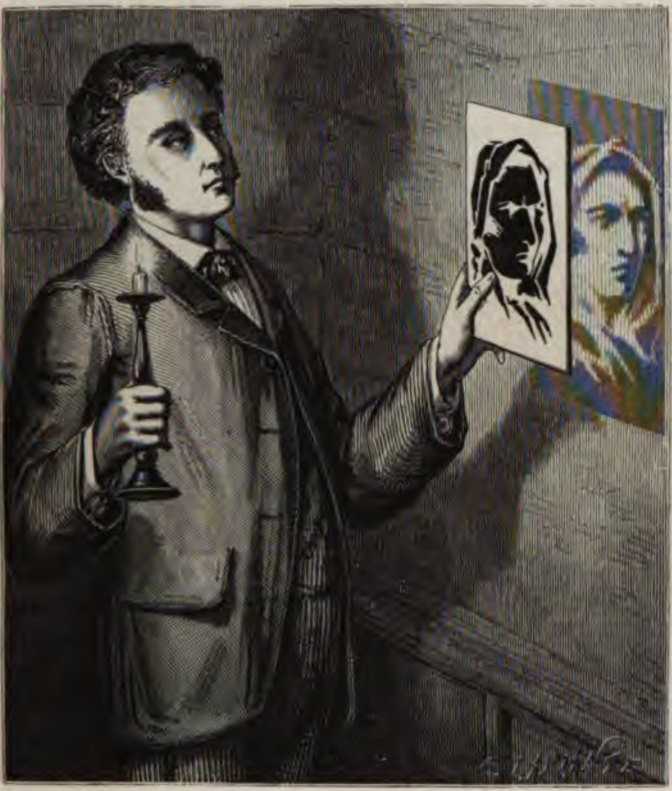

FIG. 154.—Silhouettes or perforated cards; effect of the umbra and penumbra.

to a greater extent, produces the wished-for effect (Fig. 154): again, if this distance is too great, the image becomes confused.

The propagation of light in a right line explains the phenomena observed in a dark room. Shut yourself up in a room, the window of which is completely closed, a very small hole being made in a thin part of the shutter, and let it be by this hole alone that the rays of a luminous body—the sun, for instance—are able to penetrate into the room. Then place a white screen at a certain distance from the opening, you will see a luminous spot of circular or elliptical form, which becomes larger as the distance from the screen to the opening is increased (Fig. 150). It is the image of the sun.

If instead of the solar light we permit that of a candle to enter the dark room, we see reproduced on the screen the image of the candle

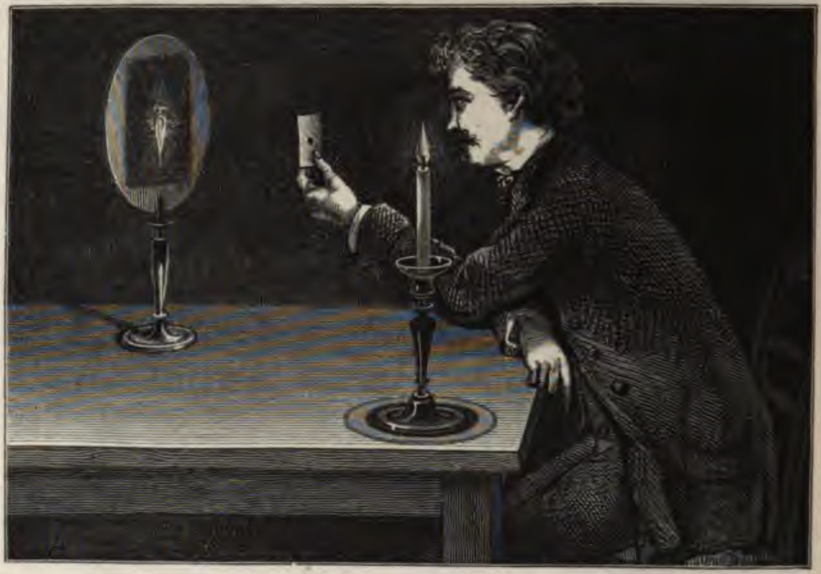

Fig. 155.—Inverted image of a candle.

and its flame, inverted. The reason of this inversion is very simple. The rays which leave the upper extremity of the flame pass through the hole, continue their passage in a right line in the dark room, and paint a luminous point at the lower part of the screen. Those which proceed, on the other hand, from the base of the flame, form their image at a higher point. The image therefore is naturally reversed, and the above explains both why this image exists, and why it has this particular arrangement. A card pierced by means of a needle gives the reversed image of a candle as shown in Fig. 155.

The form of the opening is also immaterial: round, square, or triangular, it always gives the image of the light-source with its exact form. Let us suppose the opening to be of triangular form; and allow the rays of the sun to penetrate it, receiving them on a screen placed normally to their direction. Each point of the disc will give a pencil of light which, penetrating through the hole, will mark out on the screen a section of like form to the opening, that is, triangular. All these elements will be superposed; and as there is no part of the shape of the disc which is not given, it follows that the form of the image will be circular, like that of the sun.

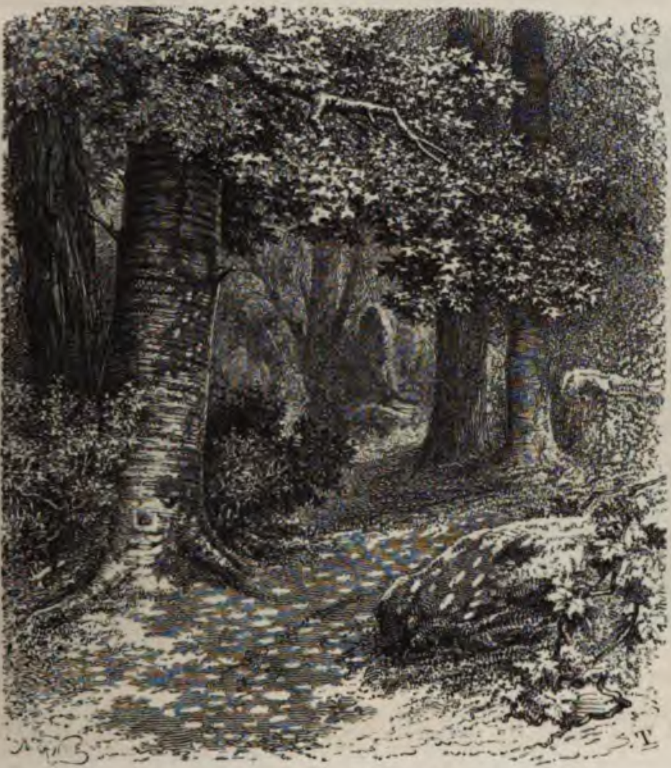

FIG. 156 — Images of the Sun through openings in foliage.

This explains why, in the shadow projected by a tree, the light which penetrates the interstices between the leaves always has a circular or elliptical form, according as the rays fall on the ground perpendicularly or obliquely (Fig. 156). During eclipses of the sun, it has been observed that these images of the luminary take the form of a luminous crescent, much more curved than the solar disc itself.

If the shutter of the dark room is opposite a landscape illuminated by the sun, or even by the diffused light given by a clear sky, each object will paint its reversed image on the screen, and a faithful reproduction of the landscape will be seen (Fig. 157). If the screen is perfectly white, all the colours and their shades will be admirably reproduced; but the image will be clearer in proportion as the opening is smaller and the landscape more distant.

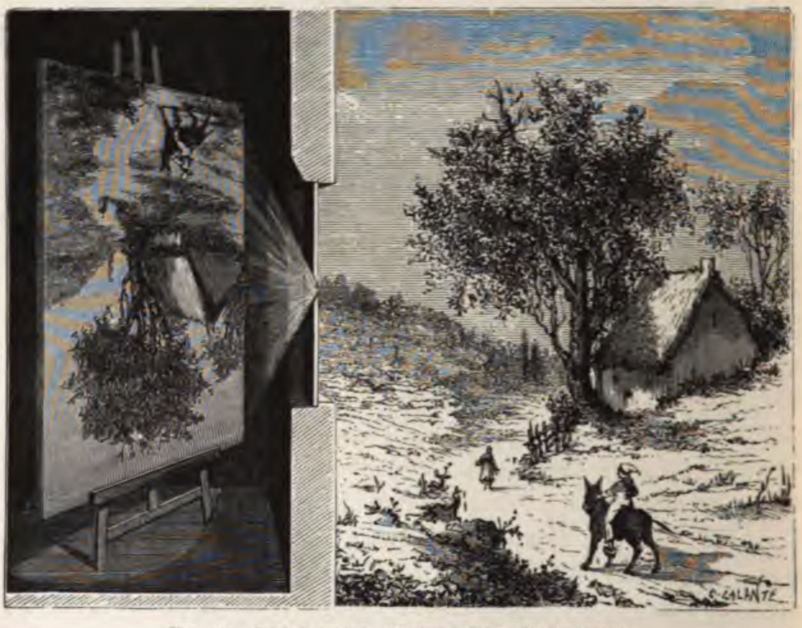

FIG. 157.—Dark chamber. Reversed image of a landscape.

By saying that light is propagated, we admit implicitly that it is not transmitted instantaneously from one object to another; that it takes a certain time to traverse the distance which separates the luminous object from the eye which it enters, or from the object which it illuminates. This truth had been suspected for some time by philosophers and *savants*, but the demonstration of it was only furnished about two centuries ago. The velocity of light is so great that it appeared at first infinite, at least for distances which could be measured on the surface of the earth. In one second, light passes through a space of not less than 300,000 kilometres, or 186,000 miles. It does not take more than a second to come from the moon (approximately); but it takes 8 minutes 13 seconds to come from the sun: a very rapid voyage, nevertheless, when we bear in mind that a cannon-ball would take nearly twelve years to accomplish it, supposing that it preserved a uniform velocity of 500 metres per second. Again, the velocity of light is 900,000 times greater than that of sound through air at 0° C., and it moves 10,000 times faster than our planet in its orbit.

How, then, have physicists succeeded in measuring such a rapid movement? We will endeavour to explain.

Let us imagine that a flash of light—for example, the ignition of a heap of gunpowder—is produced periodically at perfectly equal intervals of time, say every ten minutes. Whatever may be the distance of the observer from the place where the phenomenon takes place, it is evident that, from the first explosion, all the others will appear to succeed each other at successive intervals of ten minutes, whether the velocity of light be small, considerable, or infinite, provided that the observer remains at a fixed distance from the point where the explosion occurs.

But if, from the instant of the first explosion, the observer goes further away, it is clear that he will perceive a delay at each of the following explosions, a delay which will go on increasing and will be due to the time that the light takes to traverse the increase of distance; for instance, at the twelfth explosion, if he is 20 kilometres further off and the delay noticed is two seconds, must he not conclude that light travels 10 kilometres per second? The same inference may be drawn from an analogous experiment; if, for example, instead of a luminous flash, it was the periodical disappearance of a light which was observed.

Now a phenomenon of this latter kind takes place in the heavens. The planet Jupiter is accompanied in its movement of translation round the sun by four satellites which revolve round it in regular periods. The planes in which the movements of these little bodies take place coincide, very nearly, with the plane of Jupiter's orbit. N Jupiter, being opaque, projects behind it, that is to say in the direc from the sun, a cone of shadow, the axis of which is in the plane o orbit. It therefore follows that, in their successive revolutions ro

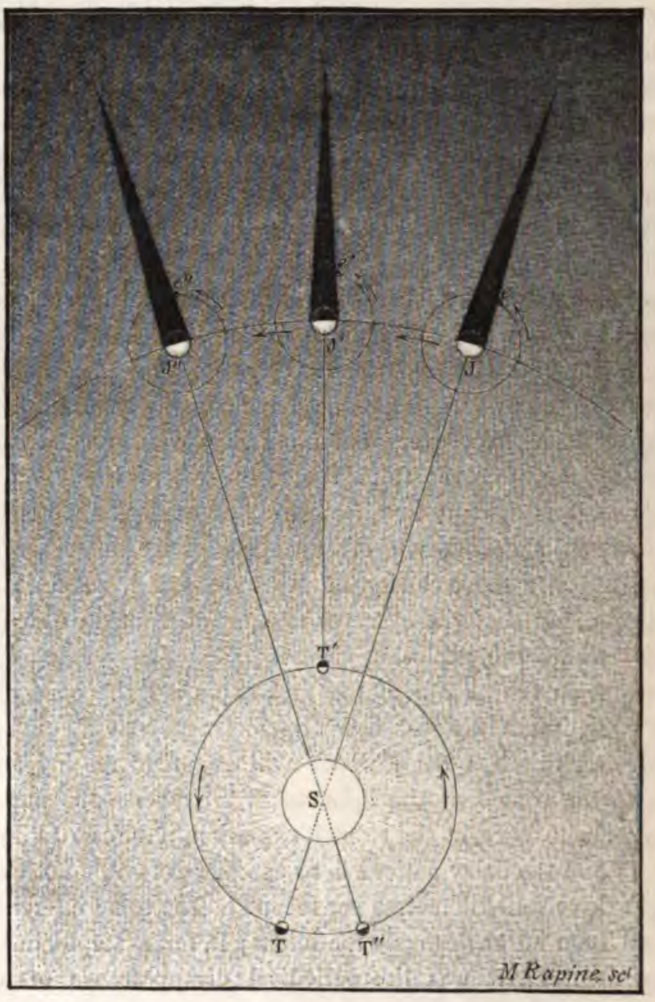

Fig. 158.—Measure of the velocity of light by the eclipses of Jupiter's satellites.

the central planet, the satellites traverse this cone at the perio their opposition. During the time of their passage through shadow, the light which these bodies receive from the sun is i cepted; in a word, they are eclipsed. The eclipses of Jupiter's satellites are very frequent, especially of those which are nearest the planet: and, from the earth, it is easy to observe their emersions and immersions by using a telescope of medium power. When the satellite drawn by its movement of revolution round the planet has just penetrated the cone of shadow, its light is extinguished: this is the immersion. It continues its course in the shadow until the moment when, coming out of the cone, its light reappears: this is the emersion. These two phenomena are not visible from the earth during the same eclipse, in the case of the two satellites nearest to Jupiter, because these satellites are hidden by the opaque body of the planet, sometimes at the moment of their immersion and sometimes at that of their emersion. Moreover, they cannot be observed in any way at the period of conjunction or opposition, the cone of shadow being entirely hidden by the disc of the planet, as is easily explained by Fig. 158. It is also easy to see why the immersions are visible to us from the period of conjunction to the following opposition, whilst the emersions, on the contrary, are visible from opposition to conjunction.

Jupiter moves in the same direction as the earth, but much more slowly in his orbit. When the earth is at T and Jupiter is at J on the prolongation of the radius vector T S, this is the period of conjunction. From this instant, the earth describing a certain arc on its orbit, and Jupiter an arc of less amplitude on his, the observer finds himself carried to the right of Jupiter's cone of shadow, and from that time he can see the immersions of the satellites. The same circumstances take place until the time when, the earth being at T′, Jupiter is at J′, also on the prolongation of the radius, but away from the sun; that is to say, until the opposition. Then, by the fact of the simultaneous movements of the earth and Jupiter, the first of these planets is carried to the left of the cone of shade projected by the second, and the emersions of the satellites are visible until the new conjunction T″, J″.

These preliminaries being understood, we can easily explain how astronomers are able to deduce the velocity of light from observation of the eclipses of which we have just spoken.

Let us take, for instance, the first satellite of Jupiter, that is to say the one nearest the planet. Its movement of revolution is known with such precision that it is possible to calculate the intervals of its eclipses with the greatest accuracy, or rather the intervals which separate either two consecutive immersions or two emersions. Now, observation proves that the duration of these intervals is not constant; that they appear to be shortened in proportion as the earth gets nearer to Jupiter, and on the other hand to be increased as it passes further away, whilst they are perceptibly equal at the two periods when the distance from the earth to Jupiter varies but little, that is to say at conjunction and opposition. If then we calculate the period of a future immersion according to the mean duration of the intervals separating two successive immersions, and compare the result of the calculation with that given by observation, it will be found that the phenomenon appears to be delayed when the earth is distant from Jupiter, and to advance, on the contrary, when it is near to it. Moreover, the delay or advance is always in exact proportion to the increase or decrease in the distance between the two planets.

It is no longer doubtful that the difference between the result of calculation and observation is really due to the time which the light takes to traverse the unequal distances which we have just mentioned. From conjunction to opposition, or from opposition to conjunction, it has been found that the successive accumulations of these differences produce a total advance or delay of about 16 minutes 30 seconds. Now, the distances T J, T″ J″ exceed the distance T′ J′ by an amount of space which is precisely the diameter of the terrestrial orbit. It requires, then, 16 minutes 30 seconds for light to travel across this interval, or, in other words, 8 minutes 15 seconds for the half, which is the distance from the Sun to the Earth; nearly equal to 146,000,000 kilometres (91,000,000 miles).

This gives, as we have before said, a velocity of 300,000 kilometres, or of 186,000 miles per second.

The discovery of the velocity of light by the eclipses of Jupiter's satellites is due to Roemer, a Danish astronomer, who explained it in a memoir presented to the Académie des Sciences in 1675. Since the time of Roemer, the discovery of aberration by Bradley at once confirmed both the moment of translation of the earth, and the successive propagation of light in space. We see that the exactness of the number which measures the velocity of light depends here on the knowledge of the sun's distance. The same thing happens when this velocity is deduced from aberration. But in the first case, it is the velocity in the vacuum of celestial space; whilst in the second case, it is that of light passing through the air. The two methods have given nearly the same results.

Lastly, during the last few years, two *savants*, MM. Fizeau and Foucault, have succeeded in directly measuring the velocity of light by purely physical means. The following are the main points of the method devised by M. Fizeau.

By means of an instrument represented in Fig. 159 he sent a pencil of luminous rays from a lamp, from Suresnes—where he was stationed—to Montmartre, where a mirror was placed, reflecting the light back again exactly to the point of departure. The light of the lamp at first fell, after having traversed a system of two lenses, on a mirror M, formed of a piece of unsilvered glass, inclined at 45° in the direction of the luminous rays. From this it was reflected at a right angle, and, after its passage through the object-glass of a telescope which made the rays of light parallel, it passed through the distance which separated the two stations. Having arrived at Montmartre, the parallel bundle of rays traversed the second object-glass and concentrated itself on a mirror which sent it back, following the same route, to the first inclined mirror. There the reflected pencil passing through the unsilvered glass, could be examined by the observer by means of an eye-piece. By this arrangement M. Fizeau was able to observe at Suresnes the image of the light placed near him,

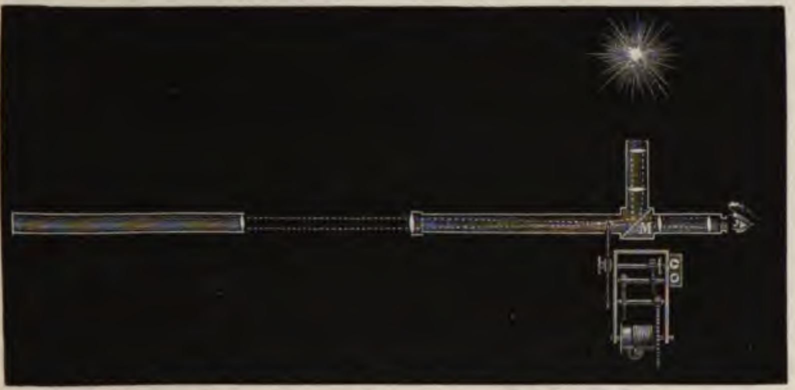

FIG. 159.—M. Fizeau's instrument or the direct measure of the velocity of light.

after the rays had made the double journey which separates Suresnes from Montmartre.

The question was, to determine the time which light took to traverse this distance. In order to ascertain this, M. Fizeau placed in the path of the rays a little in front of the mirror M and at the point where the rays, which emanated from the lamp, were brought to focus, the teeth of a wheel R, to which a clock-work mechanism gave a very rapid and uniform movement.

Every time that the movement of the wheel brought a tooth in the path of the pencil of light, this tooth served as a screen, the light was intercepted; whilst it freely passed through the space which separated one tooth from another. It was exactly as if a screen were alternately placed before and removed from the path of the light. Let us suppose that, at the commencement of rotation, the wheel, at present at rest, presented one of its openings to the passage of the light: the image reflected from the luminous point is seen clearly by the observer. If now the wheel is turned, but with such a velocity that each tooth requires to take the place of the space which precedes it a longer time than that required by the light to go to Montmartre and return to Suresnes,—what will happen? The luminous ray at its return will obviously again find free passage through the very space which it traversed at the moment of departure: the luminous point will be visible; but, in proportion as the velocity of rotation increases, the intensity of the light will diminish, because of all the luminous rays which pass through each of the intervals, there is an increasing number

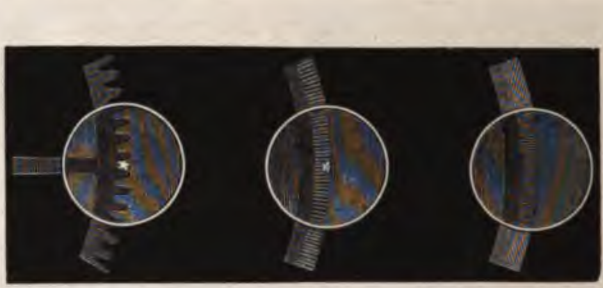

FIG. 160.—Measure of the velocity of light by M. Fizeau.

1. The luminous point seen through the teeth of the fixed wheel.
2. Partial eclipse of the luminous point.
3. Total eclipse.

which, on their return, will find the passage closed. If, at last, the velocity of the wheel is such that the time taken by one tooth to take the place of the space which precedes it, is precisely equal to that which the light takes to traverse the double distance between the two stations, there is not a single luminous ray passing through the wheel at leaving, which does not, on its return, find the passage closed; there will be a continual eclipse of the luminous point, as long as the velocity of which we speak remains the same.

This is sufficient for the purpose because an index fitted to the wheel indicates the number of revolutions which it makes per second; and the number of teeth and of spaces is known: the time which a tooth requires to take the place of a space is then known, and it will be seen that it is exactly equal to that which the light takes to travel twice the 8,633 metres which separate the two stations. M. Fizeau thus found that light travelled 196,000 miles (315,000 kilometres) a second; a result agreeing with that furnished by the observation of Jupiter's satellites, when the distance of the sun deduced from the ancient parallax of that body was adopted.

Some time after M. Fizeau's experiment, in May and June 1850, some instruments, based on the principle of rotating mirrors adopted by Mr. Wheatstone in measuring the velocity of electricity, have enabled it to be shown that light moves with greater rapidity through air than through water, and the relations of the two velocities to be determined. MM. Léon Foucault and Fizeau have each succeeded in attaining the same result. Lastly, in 1862, the first of these experimenters, modifying his first apparatus, went still further; he succeeded in measuring the time which light takes to travel the little distance of 20 metres, a time which is equal to the hundred and fifty millionth part of a second. According to later experiments of M. Foucault, the velocity of light through space is 298,000 kilometres a second, a little less than that obtained by M. Fizeau, but which agrees with that deduced from observations of the eclipses of Jupiter's satellites, adopting the new parallax of the sun.

CHAPTER III.

PHOTOMETRY.—MEASURING THE INTENSITY OF LIGHT SOURCES.

Luminous intensity of light sources, illuminating power—Principles of photometry —Law of distances—Law of cosines—Rumford's photometer—Bouguer's photometer—Determination of the illuminating power of the Sun and the full Moon —Stellar photometer.

WE all know, by everyday experiment, that the illuminating power of a light varies according to the distance at which the object illuminated is placed from the source of light. When we read in the evening by lamp or candlelight, we can also observe that, without changing the distance we are from the light, it is possible, by inclining the pages of our book in a certain way, to obtain various degrees of illumination. Lastly, if instead of one light we place many at the same distance, or, again, instead of a small lamp we substitute a very large one with a wide wick, it will be evident to us that the illumination will be augmented in a certain proportion.

The illuminating power also varies with the nature of the luminous source, other things being equal. The flame of a gas-jet appears to us much more brilliant than that which is given by an oil lamp; the light of the moon is infinitely less bright than that of the sun, although the discs of the two bodies have nearly the same apparent size.

When the intensity of the source of light is sought for, certain circumstances must be taken into account; some being inherent in the light sources themselves, others peculiar to the object illuminated, such as distance, inclination, &c. The problems relative to determinations of this nature constitute the branch of optics called photometry, from two Greek words which signify—the first, light; the second, to measure.

Nothing is more delicate or difficult than the measurement of luminous intensities. In spite of all progress realized in the science of optics, there are yet no instruments which give this measure with an exactness comparable to other physical processes. The barometer and thermometer respectively give us with extreme sensibility the pressure of the atmosphere and the temperature; the relative pitch of two sounds can be distinguished with great delicacy. Photometry is in a less advanced condition, and the comparison of the intensity of two lights yet leaves much to desire. This arises from the fact that we have no other criterion in this case than the organ by the aid of which we perceive the lights to be compared. The sensation of sight is the only judge, and, in spite of its extreme sensibility, the eye is but slightly fitted to determine the numerical relations of two or more lights, which are before it either simultaneously or successively.

Even when it has to judge of the equality of two light sources, the difficulty is great. If the observations are not simultaneous, the comparison will be the more difficult according to the interval of time which elapses between them. We must first arrange, therefore,—and that is not always possible,—that the two lights be observed together.[1]

Very frequently the brightness of the sources of light dazzles the eye, and renders it incapable of judging with the least precision; and this is the reason why physicists, instead of comparing the sources of light themselves, observe similar surfaces illuminated by these sources under similar conditions of inclination and distance. Again, the diversity of the colours of lights is a cause of uncertainty which cannot be obviated. "Between two differently coloured lights," says Sir J. Herschel, "no parallel susceptible of precision can be drawn; and the uncertainty of our judgment is greater as this difference of coloration is more considerable."

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[1] "In this manner the judgment of the eye is as little to be depended on, as a measure of light, as that of the hand would be for the weight of a body casually presented. This uncertainty, too, is increased by the nature of the organ itself, which is in a continual state of fluctuation ; the opening of the pupil, which admits the light, being continually expanding and contracting by the stimulus of the light itself, and the sensibility of the nerves which feel the impression varying at every instant. Let any one call to mind the blinding and overpowering effect of a flash of lightning in a dark night compared with the sensation an equally vivid flash produces in full daylight. In the one case the eye is painfully affected, and the violent agitation into which the nerves of the retina are thrown, is sensible for many seconds afterwards in a series of imaginary alternations of light and darkness. By day no such effect is produced, and we trace the course of the flash and the zigzags of its motion with perfect distinctness and tranquillity, and without any of those ideas of overpowering intensity which previous and total darkness attach to it."—SIR JOHN HERSCHEL.

In spite of these difficulties there have been established, either by reasoning or by experiment, a certain number of principles which have suggested the invention of various photometrical instruments, some of which we will now describe. In the present day, when public and private gas-lighting has become very general, and the want has been felt of facilitating navigation on our coasts by establishing numerous lighthouses, photometers have become instruments of which the practical utility is equal to the interest of the purely scientific problems for which they have been invented. But it is not less certain that the first processes invented for the comparison of the sources of light are due to *savants* who by no means thought of the question of practical utility. In the seventeenth century Auzout and Huyghens, in the following century André Celsius, Bouguer, and Wollaston, kept in view the interesting, although purely speculative, question of the relative brightness of the light of stars. They endeavoured to determine the intensity of the sun's light compared with that of the moon or the brightest stars.

The first principle which they enunciated was the following:—When the distance from a luminous point to the object illuminated varies, the intensity of the light received varies in the inverse ratio of the square of the distance. And, indeed, the light radiates from the luminous point in every direction with equal force; but these rays diverge as the distance increases. If they are received on the surface of a sphere of a definite radius, they will produce on one element *m* of this sphere an illumination of a determined intensity; if, continuing their path, they are received upon a sphere of double radius, the same rays which are spread on the surface *m* will be on the surface M of the new sphere. Now, geometry teaches us that M possesses four times the surface of *m*, and, inasmuch as the same quantity of light is spread over a surface four times greater, it may be concluded that its intensity is four times less. At triple the distance, the intensity is nine times less: in a word, the intensity of light diminishes as the square of the distance increases. This has been confirmed by experiment, as we shall presently see. This law holds good only if we abstract the absorption of luminous rays by the media in which they move. It is also applied to the case in which the source of light is no longer a simple luminous point, but presents an apparent appreciable surface, provided that it be distant enough from the illuminated object to allow the latter to be regarded as equidistant from all parts of the source. It follows from this first principle of photometry, that if we present to the light of a candle, for instance, a piece of white paper, and remove it further and further away to distances 2, 3, 4 times greater, the brightness will become nearly 4, 9, 16 times less. It is necessary that the paper be always placed perpendicularly to the direction of the luminous rays.

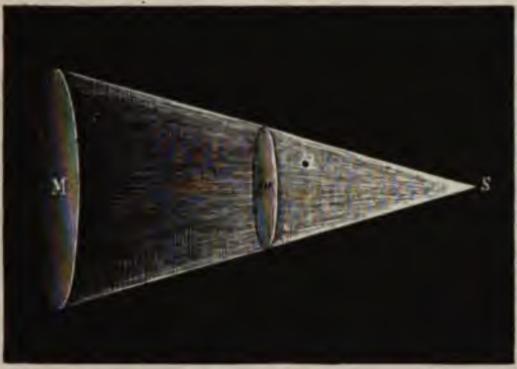

FIG. 161.—Law of the square of distances.

If, without changing the distance, the paper is inclined in one direction, it is evident that the brightness will diminish, since the same surface will now intercept a less number of rays. The quantity of light received then varies according to a law which is called the law of cosines, because it is proportional to the cosines of the angles which the luminous rays make with the perpendicular to the illuminated surface.

The foregoing remarks refer only to the illuminating power of the source of light, not to its intrinsic brightness. If this intrinsic brightness does not vary, it is clear that the illuminating power will be greater as the surface of the source itself is greater; so also in the case where the intrinsic brightness is increased, the illuminating power is increased in the same proportion.

One inference from the preceding principles is, that a light source possesses the same apparent intrinsic brightness, whatever may be its distance from the eye; for, although the quantity of light which penetrates the opening of our pupil diminishes in the inverse ratio of the square of the distance, still, as it emanates from a luminous surface, the apparent diameter of which appears smaller and smaller, and which decreases in the direct ratio of the square of this same distance, there is exact compensation, and the brightness of the source remains the same at each point. This is why the light of the planets, such as Venus, Mars, and Jupiter, appears to us always equally bright when we see them at the same height above the horizon, if the purity of the atmosphere is the same, although their distances from the earth are variable. The sun is seen from the different planets as a disc, the apparent surface of which varies from about 1 to 7,000: the quantity of light that each of these bodies receives varies in the same proportion; but the intrinsic brightness of the disc is the same at Mercury as at Neptune; if we suppose that the celestial spaces do not absorb light, and that it is subjected to the same degree of extinction in its passage through the atmospheres of the two planets.

We all know that if we look at a red-hot ball in the dark, the spherical form is no longer perceptible to the eye, and it appears like a flat disc, every portion of which shows the same luminous intensity. If, instead of a spherical ball, a prismatic bar of iron or polished silver is brought to incandescence, an analogous phenomenon will present itself. Whatever may be the position of the bar, its edges will not be visible, the brightness will be the same everywhere, on the sides presented perpendicularly to the eye as on those which are more or less inclined; in a word, the observer will believe that he is looking at an entirely plane surface. Let the bar be caused to revolve, and the movement will only be noticed by the apparent variation of width of the luminous band. The conclusion to be derived from these experiments is, that the quantity of light emitted by a solid incandescent body in a definite direction depends on the inclination of its surface to the direction of the luminous rays. Indeed, if two units of surface, one on the side of the metallic bar which fronts the observer's eye, the other on an inclined side, should emit in that direction the same quantity of light, it is quite evident that the inclined side would appear to have the greatest brightness, since the same number of rays would be spread over an area the apparent size of which is less. The sun is a luminous sphere; but its aspect is that of a disc, the intrinsic brightness of which is not greater at the border than at the centre,[1] which confirms the law we have just announced, which is called the law of the cosines, because the quantity of light emitted by equal surface areas of a light source varies as the cosines of the angles which the rays make with a normal to the surface. These are the principles upon which the measurement either of the illuminating power or the intrinsic brightness of sources of light depend.

We will now describe the instruments called *photometers*, which are used to measure these intensities. Rumford's photometer is represented in Fig. 162. It is based on the fact, that if shadows thrown on the same screen by an opaque body illuminated by two different lights have the same intensity, the illuminating powers of the two lights are equal, if they are at the same distance from the

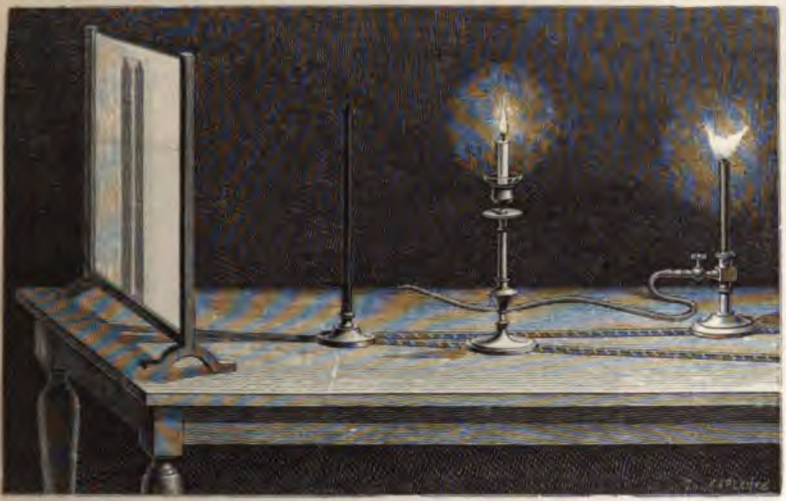

FIG. 162.—Rumford's photometer.

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[1] It is now proved that the central parts of the solar disc are the most luminous, contrary to what would be the case if there were an equal emission of light over the whole surface. Astronomers, however, have shown that this appearance is due to an absorbing atmosphere of small height, so that more light is absorbed at the borders than at the centre.

screen, or are in the inverse ratio of the squares of these distances, if they are at unequal distances. Let us suppose that we wish to compare the illuminating powers of a jet of gas and an ordinary candle. A black cylindrical rod is placed vertically in front of a screen of white paper, and the two lights are arranged so that the shadows of the rod will both be projected on the paper, nearly in contact. Then we gradually move the light which gives the most intense shadow, until the eye can no longer distinguish any difference between the intensities of the shadows. To judge better of the equality of the shadows, we look at the screen on the side which is not directly illuminated by the candle and the flame of the gas. At this moment, the luminous parts of the screen receive the rays of both lights at once, whilst each shadow is only lighted by one of them: the equality of their tints then indicates the equality of the illuminating powers of each separate source. The illuminating powers of the two lights are then, according to the first principle, in the inverse ratio of the squares of their distances from the screen.

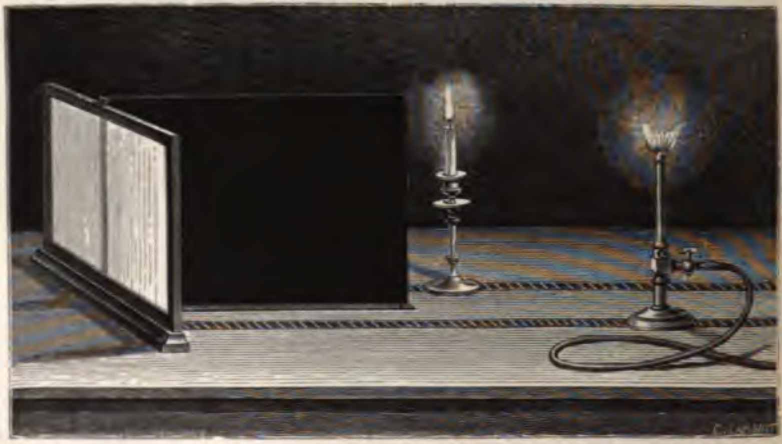

FIG. 163.—Bouguer's photometer.

Bouguer's photometer (represented in Fig. 163) is based on the equality of brightness of two portions of a surface separately illuminated by each of the light sources.

An opaque screen prevents the light of each source from reaching that part of the surface which is illuminated by the other. This surface formerly consisted of a piece of oiled paper, or ground glass.

M. Léon Foucault uses in preference a plate of very homogeneous porcelain, sufficiently thin to be translucent. The two illuminated portions are separated by a narrow line of shadow projected through the screen, and the eye placed behind judges easily of the moment when the illumination is equal. This equality once obtained, the intensities of the lights are deduced from their respective distances from the plate of porcelain. We will confine ourselves to the description of these two kinds of photometers, both of which serve to prove the law of the square of distances. The verification is very simple: it is sufficient to put on the one side one candle: it will then be found that there must be placed four at double the distance, nine at triple the distance, to obtain either equally dark shadows on the screen, or equal illumination in both portions of the sheet of porcelain. The following are some of the results obtained by the instruments:—

If we use two equal lights, two candles, for instance, and if we place one of them at a distance eight times further from the screen than the other, it will be found that the shadow of the first disappears. At this distance the intensity of its light is sixty-four times less than the other. Bouguer, to whom we owe this experiment, concluded that one light, of whatever intensity, is not perceptible to our eyes in presence of a light sixty-four times brighter. This explains to us how it is that, in broad daylight and in a clear sky, the stars are no longer visible; why from the interior of a well-lighted room we see nothing but darkness out of the windows, and again, why we can scarcely distinguish, when in full sunlight, what passes in the interior of an apartment.

Bouguer and Wollaston both tried to compare the light of the sun with that of the full moon, taking as comparison the light of a candle. They both found that the sun's light was equal to the united light of about 5,600 candles placed at a distance of 30 centimetres. As to the light of the full moon, Wollaston found it equal to the 144th part of that of a candle placed at the distance of $3^{m}\cdot 65$. Whence he concluded, by easy calculation, that the light of the sun was equal to about 800,000 times that of the full moon. Bouguer only found the number 300,000. Quoting the number obtained by Wollaston, a number which differs much from that of the French philosopher, Arago adds: "I cannot tell in what consists the enormity of this number compared with Bouguer's determination, for the method employed was exact, and the observer of incontestable ability."

It will be seen from this how difficult photometrical determinations are, especially when they refer to lights, the intensity of which is as prodigiously different as those of the sun and moon. Much has yet to be done in devising new experimental methods.

CHAPTER IV.

REFLECTION OF LIGHT.

Phenomena of reflection of light—Light reflected by mirrors; diffused light; why we see things—Path of incident and reflected rays; laws of reflection—Images in plane mirrors—Multiple images between two parallel or inclined surfaces; kaleidoscope—Polemoscope; magic lantern—Spherical curved mirrors; foci and images in concave and convex mirrors—Caustics by reflection—Conical and cylindrical mirrors—Luminous spectres.

LONG before human industry, stimulated by the requirements of luxury and frivolity, had dreamed of polishing metals and glass in order to make their surfaces brilliant for mirrors and looking-glasses, nature presented many examples of the phenomena which physicists call the reflection of light: for the surface of limpid and tranquil water, as of a pool or lake, reflects a faithful image of the country which surrounds it, the azure vault of the sky, clouds, sun, stars, trees, rocks, and the living beings who walk on the banks and sail over the liquid surface. This is on a large scale the model which industrial art has to copy, and which would enable us to study, not only conveniently but accurately, the path which light takes when, coming from luminous sources or illuminated objects, it is reflected from the surface of bodies. But the want of comprehending never precedes that of admiring and enjoying, and the discovery of the laws which govern the reflection of light was doubtless made long after the imitation of the phenomena we have just described.

Light is not always reflected in the same manner from the surface of bodies. The reflection varies according to many circumstances, among which we shall first consider the nature of the reflecting substance and the condition of its surface.

If we consider bodies whose surface is naturally smooth and polished, like liquids in a state of rest, mercury, &c., or susceptible of acquiring this quality by mechanical processes, as glass and most of the metals, &c., the reflection of light from their surface will not show these bodies themselves, but the illuminated or luminous objects which are situated in front of them. Light reflected in this manner produces the images of these objects, the dimensions and form of which depend on those of the reflecting surface; but in proportion as the degree of polish is more perfect, the light and colour will be better preserved. These are reflectors or mirrors. Physicists then say that light is reflected regularly or specularly.[1]

When light is reflected by bodies possessing a tarnished, dull, or rough surface, it does not produce images, but it shows the bodies from whence it emanates, so that each point of their illuminated surface serves for other objects the part of a luminous point. The light which a polished surface receives is never entirely reflected. If the body is transparent or translucent, a portion of the received light penetrates into the interior and traverses the substance, and is usually partly extinguished or absorbed. It is often a very small amount of the luminous rays which are reflected from the surface.

If the body is opaque, the reverse takes place; the light received is in great part reflected, but a certain quantity is absorbed by the thin strata at the surface of the body.

Let us next consider the path which light follows in the phenomenon of reflection, always supposing the medium homogeneous. Very simple experiments, which every one can verify more or less rigorously, will indicate to us the laws which govern this propagation. Let us employ a bath of mercury for a reflecting surface, and for a luminous object a star, the rays of which, coming from a distance which is practically infinite, to the surface of the earth, may be considered exactly parallel. The direction of the rays coming from the star and falling on a certain point of the mirror formed by the mercury is easily determined by means of a theodolite, the axis of which is fixed in an exactly vertical position (Fig. 165). If we look directly at the star, the line I′ S′ of the telescope indicates the direction of the incident luminous rays, and the angle S′ I′ N′, equal to the angle S I N, is the angle of incidence; that is to say, that formed by a luminous ray with the perpendicular to the surface at the point of incidence.

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[1] From *speculum*, a mirror.

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In order to find the direction of the reflected luminous rays, we must turn the telescope on its axis until we see the image of the star on the surface of the mercury bath. When the image is brought to the centre of the telescope, it is certain that the angle R′ I′ N′ is equal to the angle of reflection N I R. Thus, in reading the measure on the graduated circle of the instrument, the angle of reflection can be compared with the angle of incidence. Now, whatever may be the star

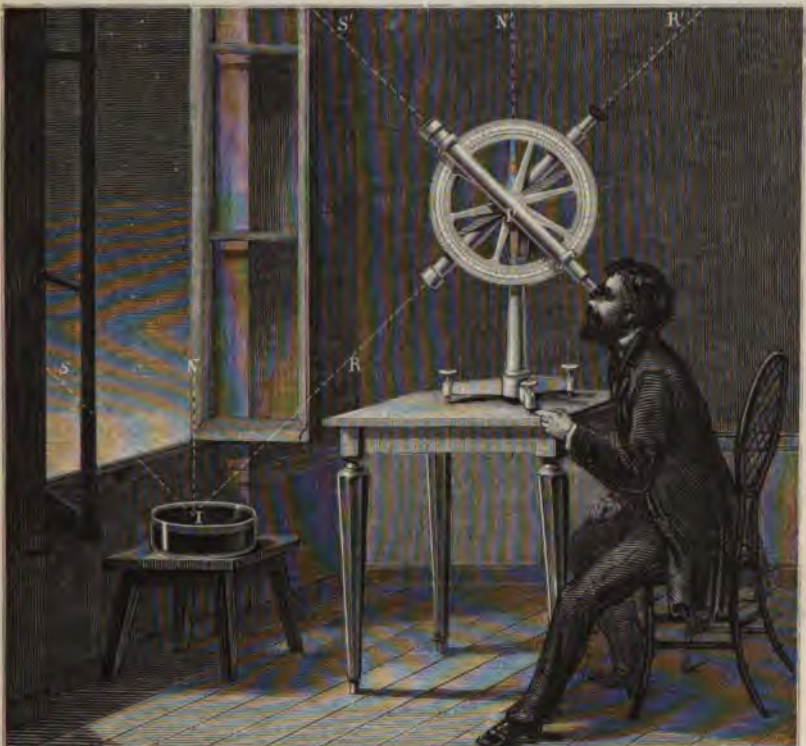


FIG. 165.—Experimental study of the laws of the reflection of light.

observed, and whatever its height above the horizon, it is always found that there is perfect equality between these angles. Moreover, that position of the circle of the theodolite which enables the star and its image to be seen evidently proves that the ray which arrives directly from the luminous point, and that which is reflected at the surface of the mercury, are both in the same vertical plane.

These two laws have been expressed by physicists in the following form:—

The angle of incidence is equal to the angle of reflection.

The incident and the reflected ray are both in the same plane, which is perpendicular to the reflecting surface.

These are two very simple laws, but they suffice to offer an explanation of the most complex phenomena, and of the action of the most varied optical instruments, whenever these phenomena and instruments have reference to the reflection of light from the surface of bodies. We shall soon be able to judge for ourselves.

In the first place we will speak of the images which appear on the surface of mirrors, that is to say, of all bodies sufficiently polished to allow the light which falls on their surfaces to be reflected in a regular manner. These images vary in dimensions and form with the form and dimensions of the reflecting surface; but it will be sufficient for us to give some idea of the luminous effects produced by plane, spherical, cylindrical, and conical mirrors.

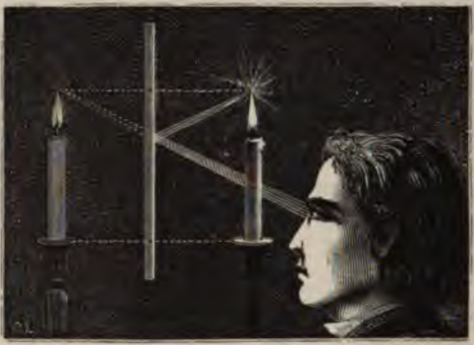


FIG. 166.—Reflection from the plane mirror. Form and position of the images.

We all know that mirrors with a plane surface—such as looking-glasses and liquid surfaces in a state of rest—show images which faithfully represent the objects which they reflect. The dimensions, form, and colour are reproduced with exactitude; the image alone is always symmetrical with the object, so that the right side of one is the left of the other, and *vice versâ*. Again, the apparent distance of the image behind the mirror is precisely equal to the real distance of the object in front of the mirror. Fig. 166 perfectly explains these conditions.

All the luminous rays which the extremity of the flame of a candle throws upon a plane mirror, diverge in every direction after their reflection from the surface of the mirror; but the equality of the angles of incidence and reflection causes these rays to converge behind the mirror at a point symmetrically situated in relation to the luminous rays. The eye which receives one of these rays will then be affected as if the luminous object were situated at the point of convergence, and he will there see the image. Whatever may be the position of the observer in front of the mirror, the position of the image will be the same, although it appears to occupy different points on the same mirror. The lower end of the candle will form its image in the same manner, and so with all the intermediate points. From this it is seen that the image of any luminous object will be formed, point by point, of all the partial images symmetrically situated behind the mirror, at distances from its surface equal to the distances of each of the points of the object.

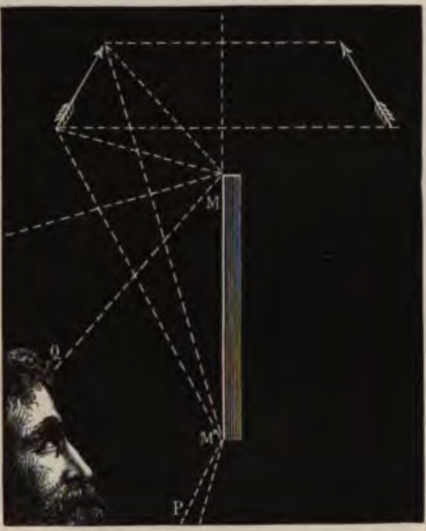


FIG. 167.—Reflection from a plane mirror. Field of the mirror.

Fig. 167 shows how the image of an object can be seen in a plane mirror, without the object being directly in front of it; it suffices that the eye be placed so as to receive the reflected rays, that is to say rays in the divergent space Q M M′ P. This is called the *field of the mirror.*

In mirrors, or ordinary looking-glasses, the form and colour of the reflected objects are generally slightly altered, because it is difficult to obtain a perfect polish and an exactly plane surface. The diffused light is then mixed with the light reflected from the mirror, and communicates to it the colour which the substance of the mirror possesses. We also observe in tinned mirrors that the objects frequently form a double image: one, the more feeble of the two, is formed on the exterior surface of the mirror; the ot the more brilliant, is that which is given by the mirror prope so called, that is to say, by the internal tinned surface. Meta mirrors have not this inconvenience, but they possess oth which are much greater: the quantity of light that they reflect not so great, and their surface tarnishes rapidly in contact w the air.

If we place two or more plane mirrors in various ways, we obt singular effects from the multiple reflections which are cast ba from one mirror to another.

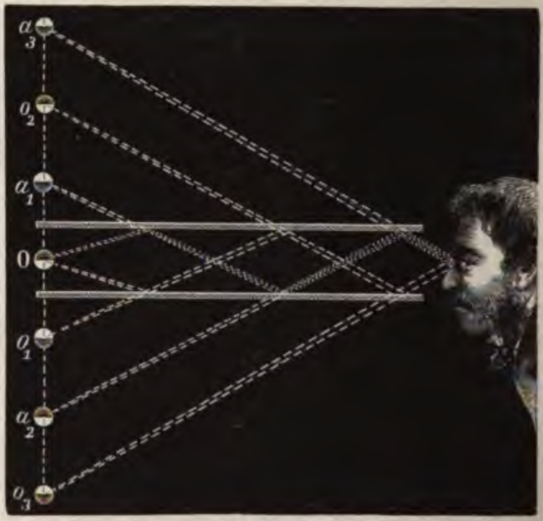


FIG. 168.—Reflections from two plane parallel mirrors. Multiple images.

The most simple of these effects is that which is produced by two plane parallel mirrors (Fig. 168). A luminous object interposed between the two mirrors shows on each of them one image, a_1, o_1, which becoming a luminous object to both mirrors, gives rise to two new images more distant than the first, a_2, o_2. These form new ones, and so indefinitely; so that with the eye conveniently placed, we shall see an infinity of images which become more and more feeble on account of the loss which the light undergoes by each successive reflection. These effects are easily observed in a room containing two parallel and opposite looking-glasses. The two series of images soon become confused when they are influenced by a luminous point;

but if we wish to distinguish them it is sufficient to look at an object the surfaces of which are of different colours and forms.

Two plane mirrors forming an angle produce images the number of which is limited and dependent on the angle. But they are all observed to be placed in a circle, having for its centre the point of intersection of the mirrors, and for its radius the distance from the luminous point. Figures 170 to 172 represent the images formed by mirrors inclined at 90°, 60°, and 45°. The first system gives three images, the second five, and the third seven. These multiple

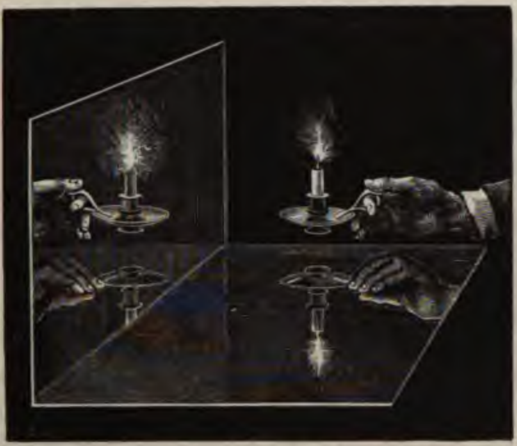


FIG. 169.—Images on two mirrors inclined at right angles to each other.

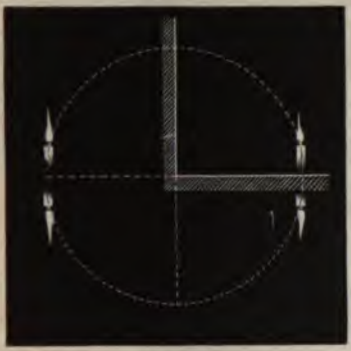


FIG. 170.—Images in mirrors at right angles (90°).

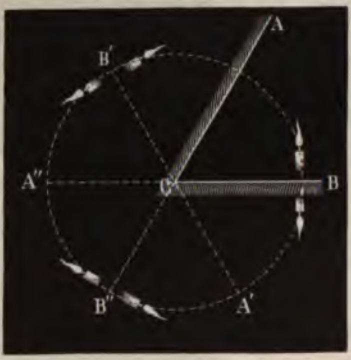


FIG. 171.—Images in mirrors at 60°.

reflections have suggested the construction of various instruments, among which may be mentioned the *kaleidoscope,* invented by Brewster.

In a pasteboard tube are fixed three plates of glass forming an equilateral prism, the bases of which are closed respectively by two parallel plates, one of transparent, the other of ground glass, between which are placed little objects, such as pieces of coloured glass. The eye, on looking through the smaller end of this kind of telescope, sees these pieces of glass, the multiple images of which are formed by reflection on the three mirrors; hence result regularly disposed figures, which can be varied at will by turning the instrument round (Fig. 173).

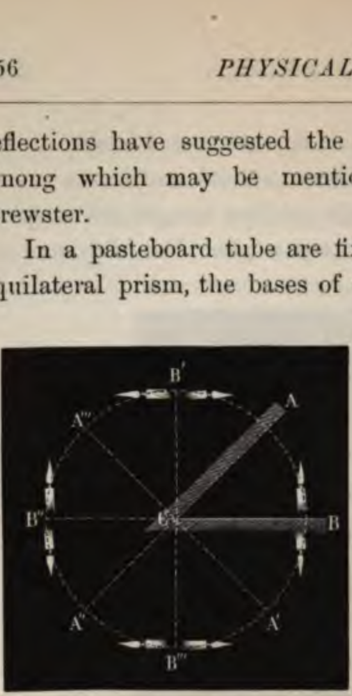


FIG. 172. – Images in mirrors at 45°.

In Brewster's kaleidosope there are only two mirrors, and the name of catoptric chamber is ordinarily given to instruments which contain three or more.

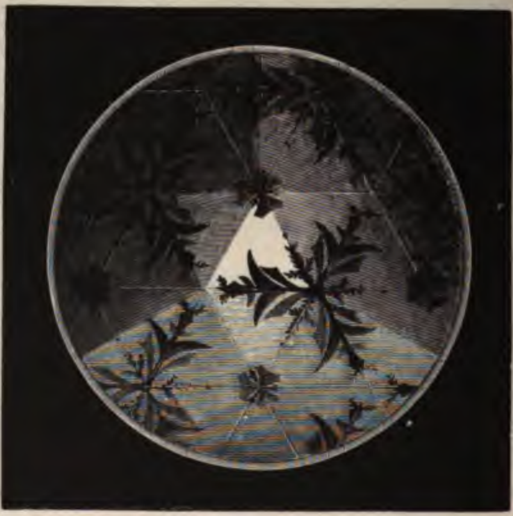


FIG. 173.—Symmetrical images formed in the kaleidoscope.

would draw us beyond the limits to which we are restricted in this first volume, and we shall confine ourselves to a simple mention of them. They are the *sextant*, the *goniometer*, and the *heliostat*. The sextant is used on board ship to measure the angular distances of two distant objects; for instance, a star and the moon's edge. Goniometers are instruments employed to measure the angles made by the sides of crystals; and the name of heliostat is given to an apparatus used to reflect the sun's rays in an invariable direction, in spite of the daily movement of the earth, which causes that body to pass over the heavens from east to west.

When light, instead of being reflected from a plane surface, falls on a polished curved one, the laws of reflection remain the same for each point of the mirror; that is to say, the angles of reflection and of incidence are always equal at each point, on either side the perpendicular to the plane tangent in the point, or from the normal to the surface at the point of incidence: moreover, the incident ray, reflected ray, and the normal, are in the same plane. But the curvature of the surface modifies the convergence and divergence of the luminous rays which, after reflection, fall on the eye: from this result particular phenomena, and, in the case of luminous objects, the formation of images, whose distance and position vary with the form of the mirrors, as also with their dimensions and distances from the objects themselves.

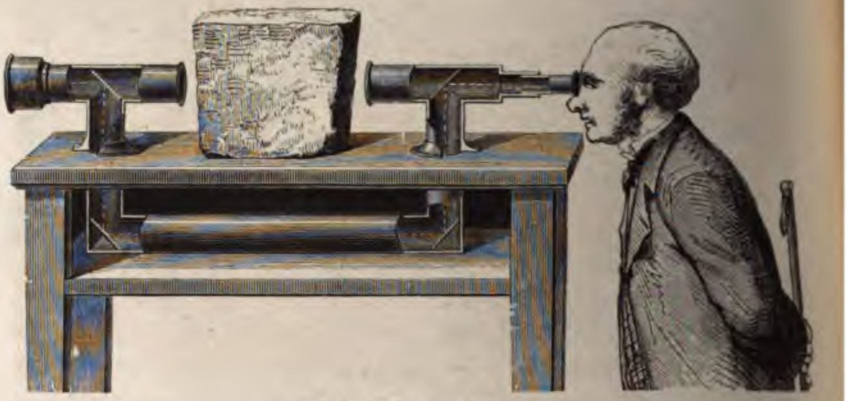


FIG. 175.—Magic telescope.

Let us now study the phenomena of the reflection of light from the surface of spherical, cylindrical, and conical mirrors.

A section through a hollow metallic sphere gives us a spherical concave mirror, if the concave surface is polished, and a spherical convex mirror, if the convex surface is polished. If the spherical portion is a tinned piece of glass, the stratum of tin is outside for a concave and inside for a convex mirror. But we have already stated why it is preferable to use mirrors of polished metal for the observation of physical phenomena. We shall speak here of these alone.

Let us observe what happens, when a luminous object, for instance, the flame of a candle, is placed at various distances from a concave mirror in a dark room. We shall in these experiments place the luminous point in the axis of figure of the mirror, that is, in the line which joins the centre of the sphere to which it belongs to the middle or the top of the spherical segment.

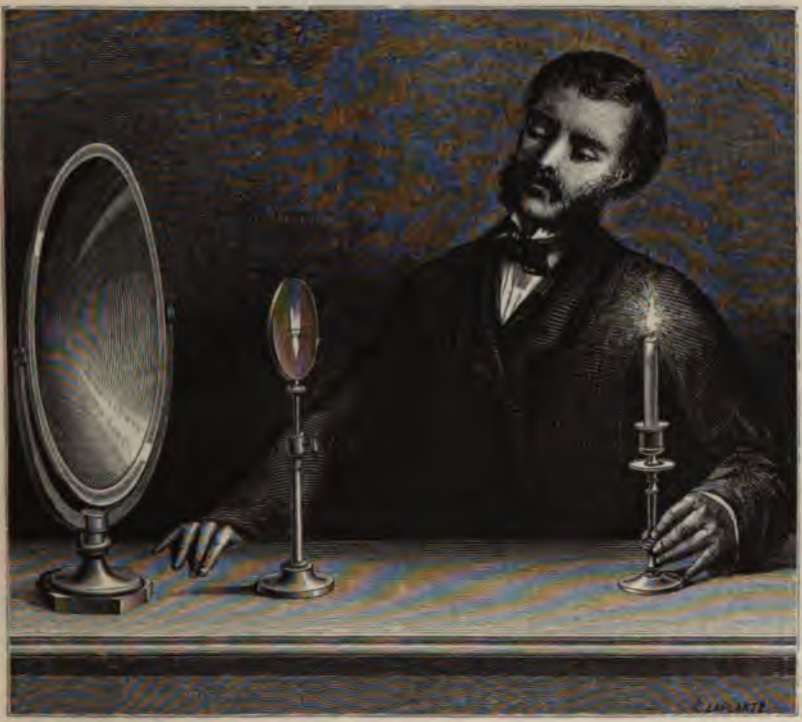


FIG. 176.—Concave mirror. Inverted image smaller than the object.

Let us first place the light at a distance from the mirror greater than the radius of its curvature. It will be easy, by the aid of a screen, to receive the reflected rays, and see that they form a sm and inverted image of the object at a point in the axis comprised tween the centre of the sphere and the centre of the light-so (Fig. 176). On moving the luminous source further from the mirror we must, in order to receive the image, approach nearer and nearer to the screen from the point of the axis called the principal focus of the mirror (we shall soon see why), and the inverted image will by degrees diminish. If the candle is brought forward from its actual position towards the centre, we observe that the image, still inverted and smaller than the object, will gradually get larger as it approaches the centre. If the candle comes to the centre, the image will arrive there at the same time, and will be blended with it in position and size. If we now continue to bring the candle nearer to the mirror, we cause the image to pass beyond the centre; it becomes larger and larger, always retaining its reversed position. In proportion as the object approaches the principal focus the image increases in size and becomes more and more diffused, until it is too large to be received on the screen. When the source of light reaches the focus, the image is situated at an infinite distance and has therefore completely vanished.

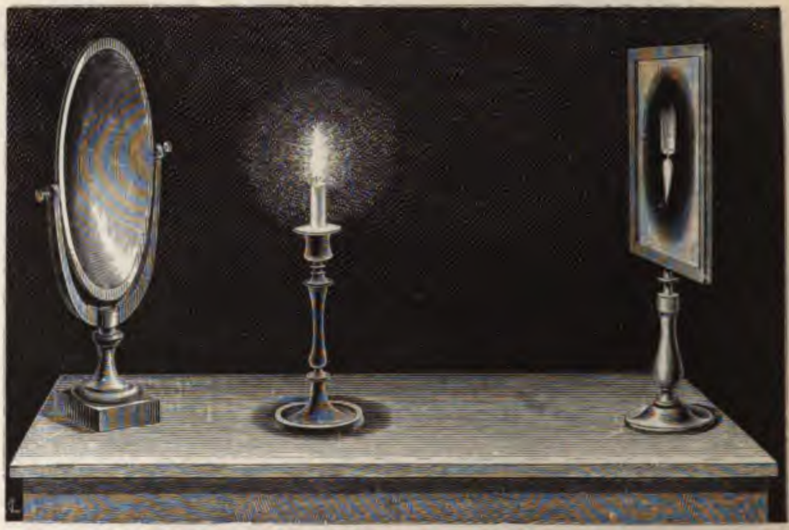


FIG. 177.—Concave mirror. Inverted images, larger than the object.

Thus far, the image of the luminous object has been real, that is, it has actually existed in the air, at the point where it is formed, and the reunion of the luminous rays has materially reproduced, so to speak, the form and colour of the object. We have also been able to receive this image on the screen. This is no longer the case, however, if we place the luminous object at a less distance than the principal focus of the mirror. The real image then exists no longer; but the eye still perceives behind the mirror, as in plane mirrors, an image of the candle: this is called a *virtual image*. It is upright and larger than the object, as shown in Fig. 178, and its apparent dimensions go on diminishing, in proportion as the light is brought nearer to the mirror. It would have the dimensions of the object itself, if it touched the reflecting surface. These various phenomena can be easily observed by the concave mirrors used for the toilet, the curvature of which is calculated in such a way that, at a short distance from the mirror, the observer, who is at the same time the object, finds himself in the position described in the preceding experiment: in this case, he sees his figure increase or diminish. On going further and further away from it, he will see reproduced, in inverted order, the phenomena above mentioned.

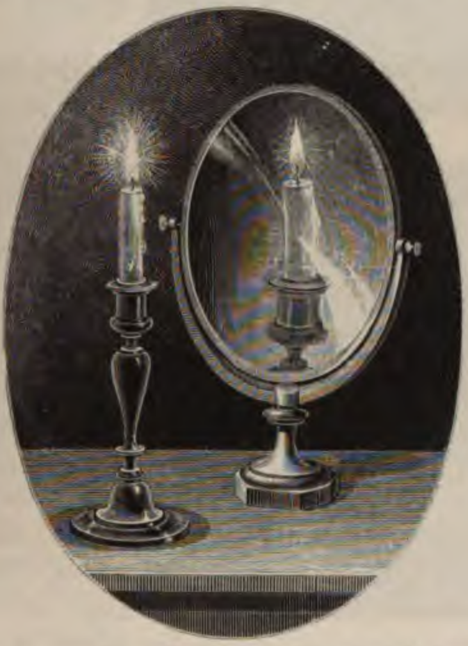


FIG. 178.—Concave mirror. Virtual images, erect and larger than the object.

Let us now return to these phenomena, and see how the laws of the reflection of light account for the various conditions which characterize them. For this purpose we must determine the path which a ray or luminous pencil follows, when it is reflected from the surface of the concave mirror.

Fig. 179 shows a cylinder of parallel, luminous rays, that is, rays which have emanated from a point situated on the axis of the mirror at a distance which may be considered as infinite. It is thus with the light which comes from the sun, stars, or even, on the surface of the earth, from an object at a distance, compared with the radius of curvature of the mirror.

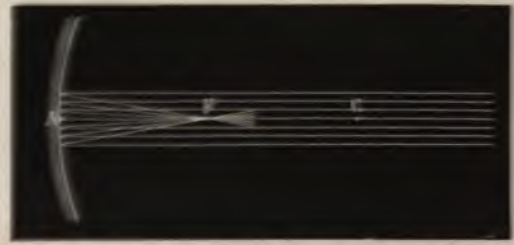


FIG. 179.—Concave mirror. Path and reflection of rays parallel to the axis. Principal focus.

Both geometry and observation agree in proving that all such rays when reflected cut the principal axis at a point situated at an equal distance between the centre C and the apex A of the mirror. Their reunion produces in F, the principal focus, an image of the point, which the eye will perceive there, since the divergent rays which penetrate our organ of vision will produce the same effect as if they issued from a real luminous object, situated at the focus. The phenomenon is the more exact as the surface of the mirror is smaller, that is, as the angle of the cone, having its highest point at the centre C of the mirror while its base is the mirror, is smaller. This angle must not exceed 8 or 10 degrees. If the mirror is spherical, the curvature is the same at each of its points; and the reflected rays will then follow a similar path in relation to the secondary axis, that is to say, to the right lines which join each point of the mirror to the centre. There are endless secondary foci on these axes, situated like the principal focus, at equal distances between the centre and the mirror.

Figs. 180 and 181 show the path of the luminous rays, when the object is situated at a distance which is not infinite, and which lies near the mirror.

The equality of the angles of reflection and incidence indicates in these various instances how the points of convergence of the rays, either on the principal or on the secondary axes, are situated at the very points where experiment has shown us that the images are formed.

Indeed, if the luminous point is at S (Fig. 180), beyond the centre of the mirror, a ray S I is reflected in I *s* and cuts the axis between the centre (C) and the focus. Bringing the luminous point now to the centre itself, the rays fall normally, and follow, after reflection, the course which they at first took from the light: the luminous point and its focus then coincide. If the point still approaches the mirror, but to a less distance than the principal focus, the reflection takes place on the axis beyond the centre.

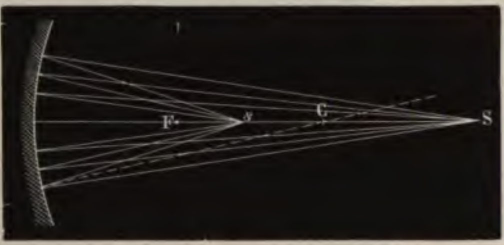


FIG. 180.—Concave mirror. Conjugate foci.

It is evident, and experiment also confirms the fact, that if the path of a luminous ray is S I *s* (Fig. 180) from the object S to the focus *s*, the path will be exactly the reverse when the ray starts from the point S, so that the points *s* and S are alternately foci one of the other. These are called *conjugate foci.*

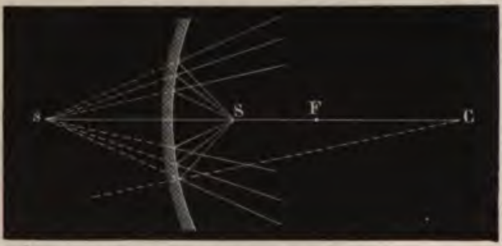


FIG. 181.—Concave mirror. Virtual focus.

The conjugate focus of the principal focus is infinite; in other words, the rays which emanate from this point are sent back parallel to the axis of the mirror. At the points situated between the principal focus and the mirror, the focus is virtual, because the reflected luminous rays are divergent (Fig. 181): we can no longer therefore consider them as conjugate foci.

Lastly, the two figures 182 and 183 show how, in the one case, the images are real, inverted, and smaller than the object, and in the other, upright, virtual, and larger than the luminous object. To construct the images geometrically, and to account for their positions and dimensions compared with those of the object, the images are sought at each extreme point A, B. To this end we join A C, B C (these are the secondary axes); then, the rays parallel to the principal axis

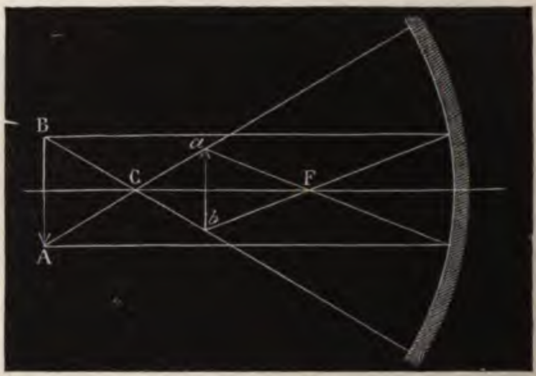


FIG. 182.—Concave mirror. Real and inverted image of objects.

are reflected to the focus F. The points of contact of the reflect rays with the corresponding secondary axis give *a* and *b*, images the extremities of the object. This construction is easily follow by means of the figures.

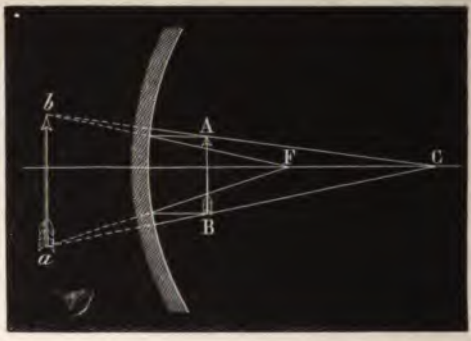


FIG. 183.—Concave mirror. Erect and virtual image of objects.

In convex mirrors, the foci and images are always virtual; an this fact is accounted for, if we follow the path of the rays and luminous pencils for each different point of a luminous object. We als see why, in these mirrors (Fig. 185), the image is upright and alway

ller than the object. The dimensions, moreover, become smaller
the distance from the object to the mirror augments. If the
ace of the mirror is very large, a disfigurement is observed,
h is more apparent as the surface is increased in extent. Any
may see this by looking into the polished balls which are
d in gardens, and in which the surrounding distant country
flected.

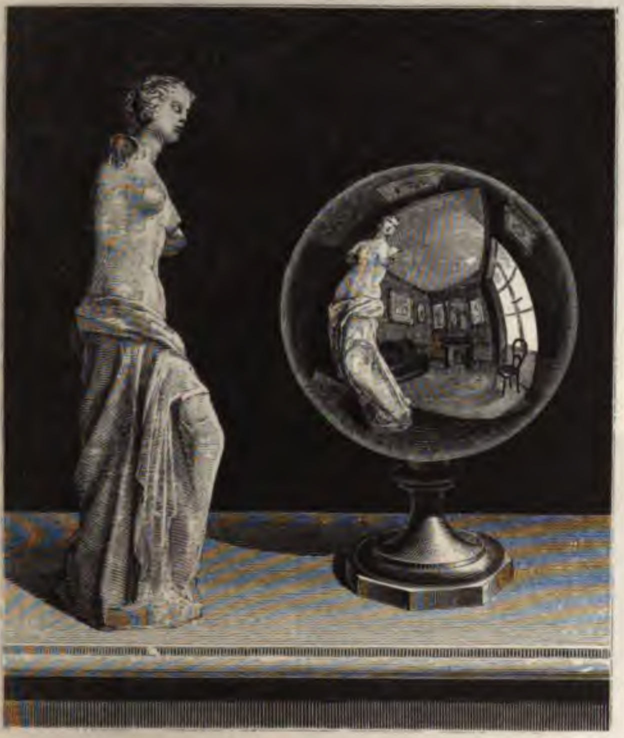


FIG. 184.—Upright virtual image in convex spherical mirror.

hen we examine, in a spherical mirror, the path of the reflected
proceeding from a luminous point, situated on the axis at any
nce, we see that these rays successively cross each other, first on
axis in its different points, then beyond the axis, in such a
ner that the points of intersection form a surface which geometers
a *caustic*. At all the points of this surface the light is more
entrated than elsewhere, and its maximum concentration is at

the focus of the given point. The caustic varies in form with the position and distance of the luminous point; but the existence of it can be proved by experiment.

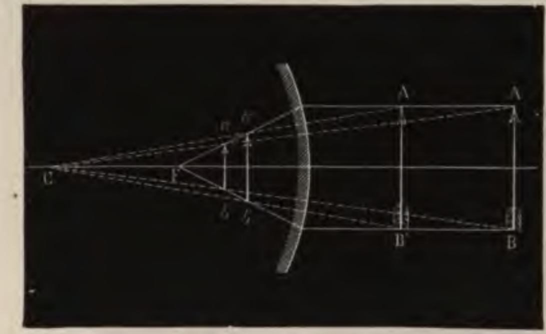


FIG. 185.—Convex mirror. Erect and virtual image.

Place a screen of white cardboard, cut so as to take the form of the mirror. When this is exposed to the light of the sun, or to that of a lamp, we perceive on some portions of the screen a brighter light, the outlines of which indicate the form of the caustic, which is evidently the same whatever may be the position of the screen as regards the centre. A circular metallic plate, polished inside, and placed on a plane, would in the same manner indicate the form of this curve for a cylindrical mirror (Fig. 186). This experiment is due to Brewster.

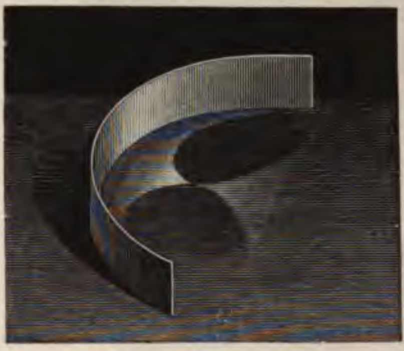


FIG. 186.—Caustic by reflection.

When a glass full of milk is exposed to the rays of the sun, or still better, as Sir J. Herschel states, a glass full of ink, we perceive on the surface of the liquid a bright curved line; it is the intersection of the caustic of the cylindrical concave mirror, which the glass forms with the limiting plane of the liquid at the upper surface (Fig. 187).

In optics parabolic concave mirrors are largely employed. These possess the property of concentrating rays parallel to the axis of the parabola to the focus of this curve, whatever may be the angle of the mirror, and they also send back in parallel lines all the light from a luminous object situated at the focus. Spherical mirrors only produce this result when the surface is very small.

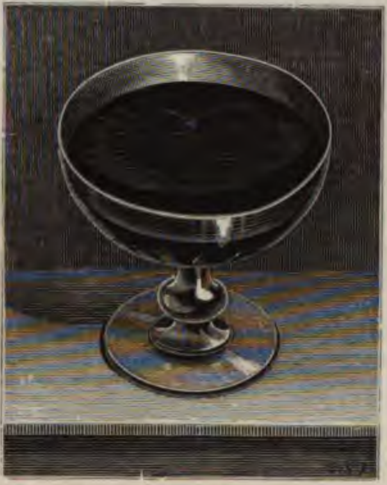


FIG. 187.—Caustic by reflection.

Convex or concave cylindrical mirrors produce images in which the dimensions of the objects are not altered in the direction of the length of the cylinder; but which, on the contrary, are varied along in a direction perpendicular to the first, that is to say, along the circumference of a section. The rays reflected along a line parallel to the axis follow the path which they would take in a plane mirror; those which are reflected on a circumference follow the path which their reflection from a spherical mirror would produce. If the cylinder is convex, the images will always be narrower in the direction of its width; if concave, they will sometimes be narrower and sometimes wider, according to the distance of the object.

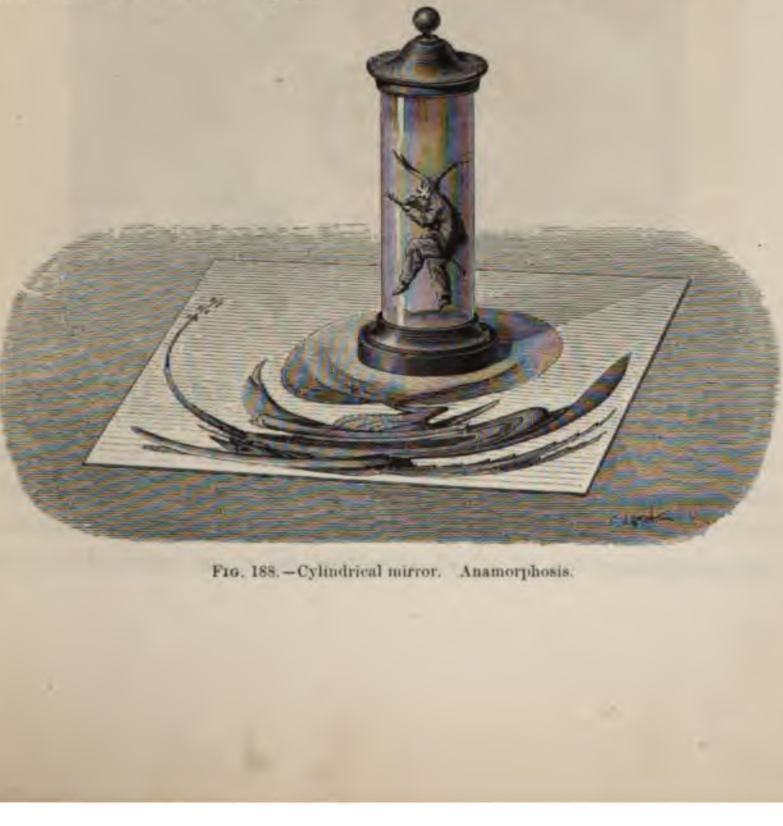


FIG. 188.—Cylindrical mirror. Anamorphosis.

In convex conical mirrors the reflected images are disfigured in the direction of the circumferences, and as the degree of curvature changes from the base to the apex, a narrowing in the dimensions is produced, which is more considerable as they approach the apex. If the conical surface were concave, the form of the image would be pyramidal, but for certain positions of the object it would be enlarged.

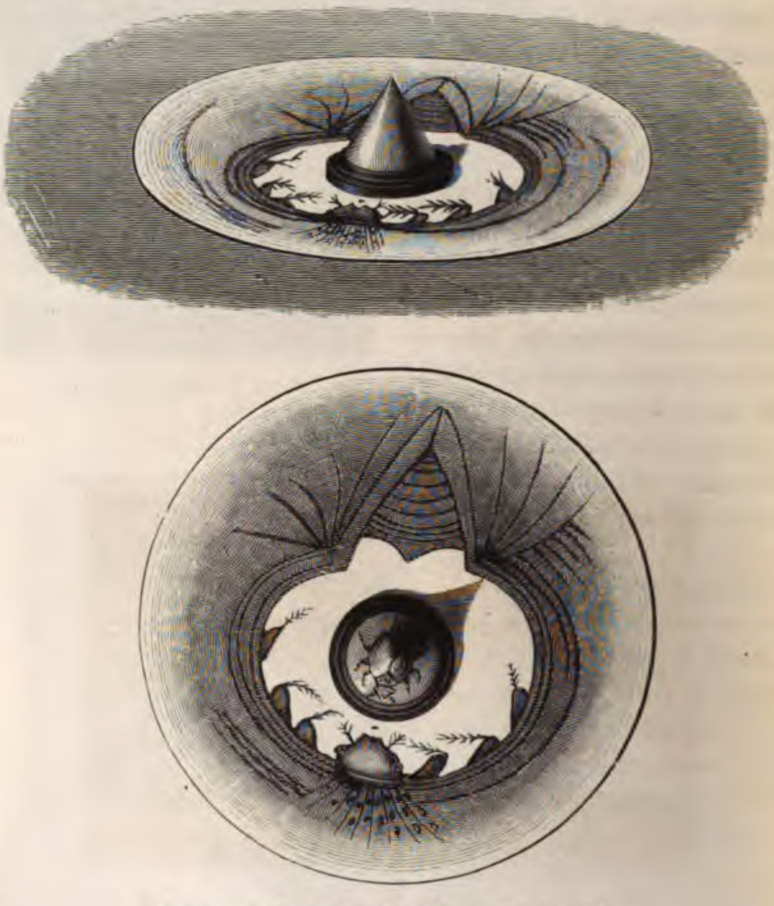


FIG. 189.—Reflection on conical mirrors. Anamorphosis.

In both these mirrors the reflection of luminous rays always takes place rigorously according to the laws which we have stated; so that we can take odd and deformed drawings, in which the eye cannot distinguish any figure, which nevertheless, when reflected in cylindrical and conical mirrors, present a faithful representation of known objects. The name of *anamorphosis* is given to this changing of forms, and opticians have pictures which they sell with conical or cylindrical mirrors, in which the lines and colours have been combined to produce regular images of landscapes, persons, animals, &c. (Figs. 188 and 189).

We have, in what has gone before, solely considered light reflected regularly from the surface of polished bodies; and the phenomena produced by this reflection show sufficiently, as we have stated above, that if the degree of polish were perfect, the reflecting body would be invisible to us. We should see the more or less disfigured image of the luminous objects which surround it, but we should not see the mirror itself. And if, with the exception of the sources of light, all bodies were in the same condition, we should only see an indefinite multitude of images of luminous bodies, of the sun, for example, without seeing anything else. In a dark room, if the solar rays fall on a mirror, the surface of this latter gives a dazzling image of the sun; but the other points of the reflecting body are only slightly visible by the irregularly reflected or scattered light. It is this light which enables the mirrors to be seen from all parts of a dark room.

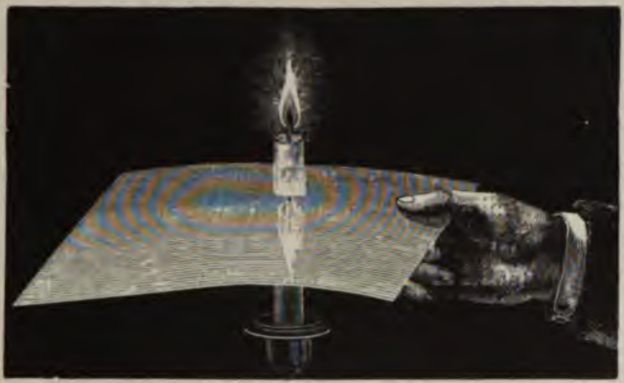


FIG. 190.—Light reflected very obliquely.

The proportion of specular and scattered light reflected by a body varies with the polish of its surface, and also with the nature of the body, its colour, and, lastly, with the angle of the incident rays. A piece of white paper reflects light in every direction; but its whiteness is brighter the more perpendicularly it is exposed to the source of light. Moreover, if the observer is placed so that he can examine the surface of the paper in directions more and more oblique, the brightness of the scattered light diminishes, but by way of compensation the eye receives an increasing number of rays regularly reflected. It is for this reason that on placing the flame of a candle very near the surface of a sheet of paper, and looking at it obliquely towards the candle, that a very distinct image is seen of the reflected flame as in a mirror.

When we say that scattered or diffused light is light reflected irregularly, we do not mean that the rays of which it is composed follow other laws, during reflection, than light reflected by mirrors. The irregularity which it undergoes proceeds from the roughness of the surface of the dull rough bodies, which receive the light under varied angles of incidence and disperse it in every direction. When such a surface is looked at very obliquely, the roughnesses hide each other, and the rays emanating from parallel sources in the general direction of the surface become more and more numerous, which explains the increasing proportion of light regularly reflected. That the quantity of light reflected by means of mirrors varies with the condition of their surface is not to be doubted. A piece of polished glass becomes a mirror; unpolished, it would scarcely scatter the diffused light. Wood, marble, horn, and numerous other substances are the same. But the reflecting power, if we give this name to the property to reflect light to a greater or less extent, varies, with equal degree of polish, according to the nature of the substances and the angle of incidence. Of a hundred rays of light received by water, glass, polished black marble, mercury, or speculum metal, with an incidence of 50°, water reflects 72, glass 54, marble 60, and mercury and speculum metal 70. If the incidence augments, the number of reflected rays diminishes for the first three bodies in a rapid proportion, and at the most is no more than 2 or 3, at from 60° to 90°; whilst, under this latter incidence, mercury reflects 69 rays out

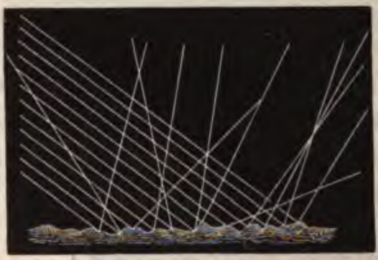


FIG. 191.—Irregular reflection or scattering of light on the surface of an unpolished body.

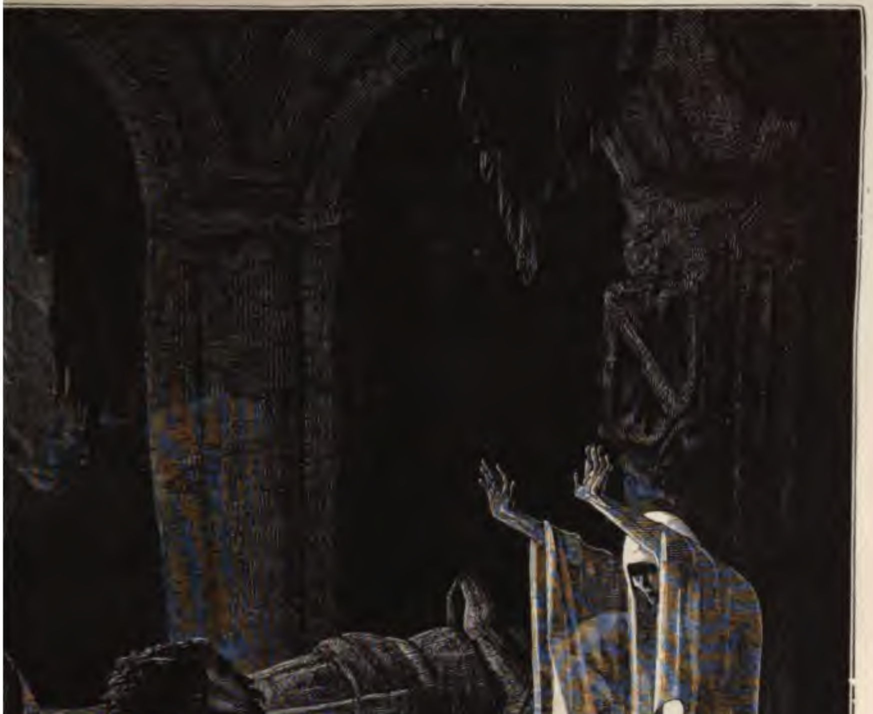


FIG. 192.—The Ghost (produced by reflection).

of 100. Dark-coloured substances reflect only a little light. Lamp-black does not scatter light, and reflects but a small amount.

When light is reflected from a polished but transparent surface, images are produced, but they are very feeble, as a great part of the incident light passes through the substance. This is the reason why mirrors and ordinary looking-glasses are tinned at the back, and the images are thus formed on an opaque body of good polish.

But untinned glasses could be used, and they give good coloured and very bright images when the objects which they reflect are well lighted, and when the space which surrounds them is at the same time in relative darkness and receives little or no diffused light. Such is the principle of the fantastic apparitions known at theatres as 'Ghosts' (Fig. 192), and which have been recently used with success in the drama.

The room in which the spectators are seated is in darkness, and the stage, separated from the room by a sheet of plate glass,

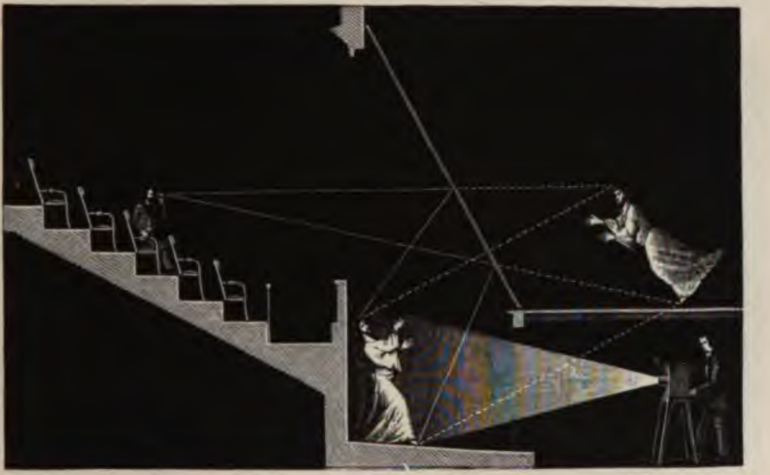


FIG. 193.—Arrangement of the unsilvered glass and the position of the Ghost.

is so slightly lighted up, that the glass is quite invisible. By giving to this an inclined position (Fig. 193), it reflects the image of a person who is strongly illuminated and stands under the front part of the stage, called the first sub-stage. The actor is seen apparently on the stage by the spectator as a virtual image, animated, and the actions of the performer can thus be seen in a way to delude the spectators and make them believe in the appearance of a real intangible phantom. The necessity of giving to the glass an inclined position, in order to make it reflect, causes the ghost to appear inclined towards the spectators, and this defect is especially perceptible to the spectators sitting at the sides.

CHAPTER V.

REFRACTION OF LIGHT.

Bent stick in water; elevation of the bottoms of vessels—Laws of the refraction of light; experimental verification—Index of refraction—Total reflection—Atmospheric refraction; distortion of the sun at the horizon.

WHEN a straight stick is thrust into clear water, that part of it which is beneath the liquid does not appear to be continued in a straight line. The stick seems to be bent from the surface of the water, and the end which is immersed rises as if it had diminished in length. If the stick is placed vertically, or if the eye receives the visual rays in a direction which causes it to be seen as if it were vertical, the stick no longer appears bent, but

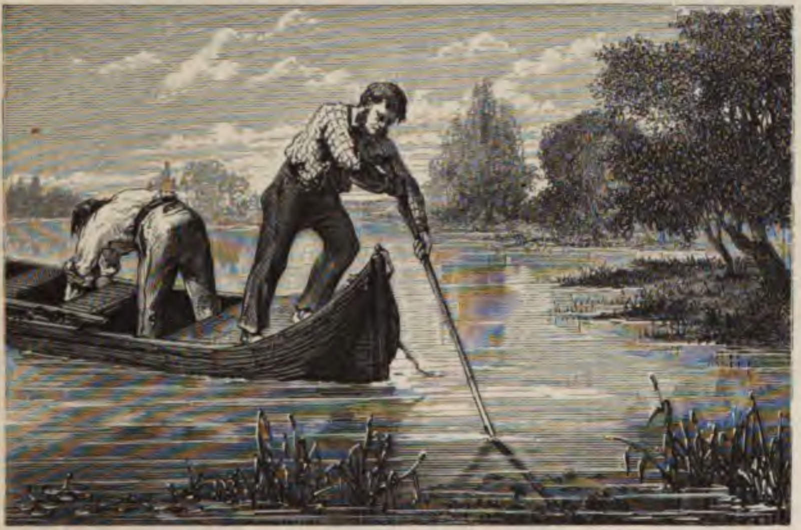


FIG. 194.—Phenomena of refraction of light. The bent stick.

simply shortened. This phenomenon is easily proved by putting the end of a pencil into a tumbler full of water.

If before filling a vessel with transparent liquid we look at the bottom of the vessel over the edge from a fixed position, and if, without removing the eye from its place, water is poured gently in, the bottom of the vessel appears to rise gradually, and at last seems much higher than before.

To make this experiment more evident, put a piece of money on the bottom of the vessel in such a position that the edge of the vessel entirely hides it. As the level of the water rises the object becomes visible and appears to rise with it, and takes the apparent position indicated in Fig. 195.

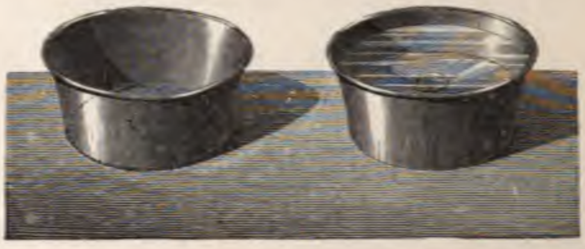


FIG. 195.—Refraction of light. Apparent elevation of the bottoms of vessels.

We have all, moreover, noticed that objects seen through a flask of clear water appear enlarged, distorted, and removed from their real position. If we follow the movements of fishes as they swim about in glass globes, it is surprising to see these animals, sometimes disappearing, sometimes becoming considerably larger, and sometimes gradually diminishing, until we see them in their actual dimensions.

All these phenomena are due to what physicists call the refraction of light—that is to say, to the deviation which luminous rays undergo when they pass obliquely from one medium into another—for example, from air into water.

When light leaves a luminous or illuminated object it moves in a right line—as we have just seen—provided that the medium through which it passes is homogeneous. Thus, the rays which enable us to see the end of the stick in the water are rectilinear so long as their passage is through water, which is a homogeneous medium. The path followed by the same rays in leaving the liquid surface and passing to our eye is likewise rectilinear, because it takes place through another homogeneous medium. But the second direction is not a continuation of the first, and the complete course followed by the luminous rays forms a broken line, the angle of which has its highest point at the common angle of incidence, at the separating surface of the two media.

Similar phenomena take place in all kinds of liquids, in transparent solids like glass, and also in gases; only, as we shall presently see, the deviation varies with the nature of the medium.

The principal phenomena connected with the refraction of light were examined long ago, and the appearance of objects when seen through clear water was doubtless observed in very remote ages.

The ancient astronomers, Ptolemy for example, noticed the effects of atmospheric refraction, that is, the deviation which the luminous rays from the stars undergo in passing from the vacuum of planetary space through the denser medium of our atmosphere. But it was not until the commencement of the seventeenth century that a young Dutch geometer, Willebrod Snell, discovered the cause of this deviation, and the laws which govern the passage of a luminous ray when it passes obliquely from one homogeneous medium to another. These laws sometimes bear the name of Descartes, because this great man discovered them in his turn, or at any rate explained them under a form which is still retained in science.

Let us examine the nature of these laws. In order to prove them experimentally, a ray, or a bundle of rays, is caused to fall obliquely on the surface of a liquid contained in a semi-cylindrical glass vessel placed within a graduated circle, and the angle which the path of the ray makes with the vertical is then measured: this is the *angle of incidence*. The ray enters the liquid, is then broken or refracted, and is seen to approach the vertical line. The *angle of refraction* is smaller than the angle of incidence.

If we vary the angle of incidence, the angle of refraction varies also; and we do not at once perceive the relation which exists between these variations. But because the refracted ray is always in the plane of the graduated circle as well as the incident ray,—and it is the same with the vertical,—it follows that the first law can be determined, which is as follows:—

When a luminous ray passes obliquely from one medium into another, it is bent aside, and both the incident and the refracted ray *remain in the same perpendicular plane, normal to the surface of separation of the medium.* We may also add, that if the ray of light enters perpendicularly to the surface, it continues its path in the same direction. There is no refraction for the normal incidence.

Fig. 196 represents the instrument as arranged for proving the second law.

The incident ray coming from the sun, for instance, falls at I on a mirror inclined in such a manner as to reflect it in the direction

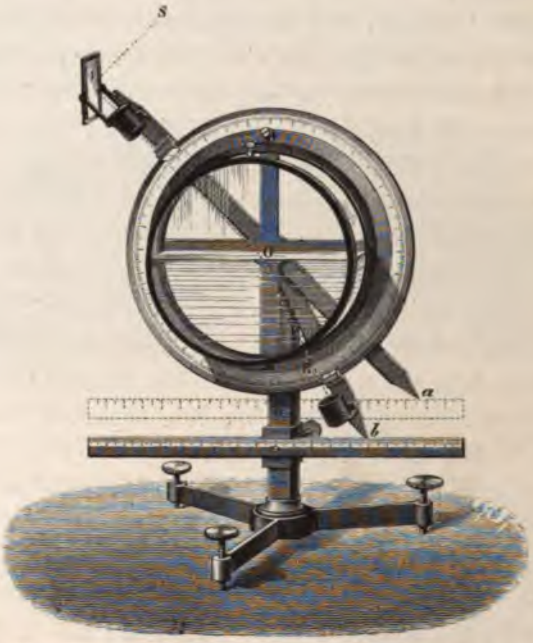


FIG. 196.—Experimental demonstration of the laws of refraction.

of the centre through a little hole in a diaphragm. An index, furnished with a point at its extremity, indicates the direction of the incident ray, and the line o a can be measured on the horizontal divided scale, which can be moved up or down. This line, or, better, its relation to the length of the ray o a, is what geometers call the *sine of the angle of incidence.* Another index, also furnished with a diaphragm pierced with a hole, receives the refracted luminous ray after its passage through the water, and o b is measured on the scale, which gives *the sine of the angle of refraction.* Let us observe that the luminous ray, on emerging from the water into the air, does not undergo a new refraction, as it passes out by an incidence normal to the surface of the cylindrical vessel.

Let us suppose that the first observation gives us two sines, such that, by dividing that of the incidence by that of the refraction, the quotient or result is the number 1·335. If we repeat the experiment several times, changing the direction of the incident ray, we find in each fresh experiment the quotient of the sines of incidence and refraction will continue to be 1·335; and it will be the same as long as the two media are air and water. But this number, which is called the *index of refraction*, varies when one of the media is changed or when both change; thus, from air to glass, the index of refraction is no longer equal to that from air to water. It has also been found convenient to calculate the indices of all transparent bodies, on the supposition that the light passes from a vacuum into each of them. By this means absolute indices are obtained. Generally speaking, the refraction increases with the density of the second medium, although there are many exceptions. Thus, the refractive power of a medium very usually increases with its density.

The second law of refraction of light may be thus stated:—

For the same two media, the quotient of the sines of the angles of incidence and refraction is a constant number, whatever the incidence may be.

The laws we have just studied indicate the path which light follows when luminous rays pass from one medium to another. But this path, as both reasoning and experiment prove, remains the same if the light passes from the second medium into the first. Then the incident ray becomes the refracted ray, and *vice versâ*. For example, if the luminous point is in the water at S, the ray which falls at the point I of the surface will be deviated from the perpendicular, following the direction I R; the path S I R will be the same, only reversed, as if the incident ray had been at R I; so that the angles of incidence

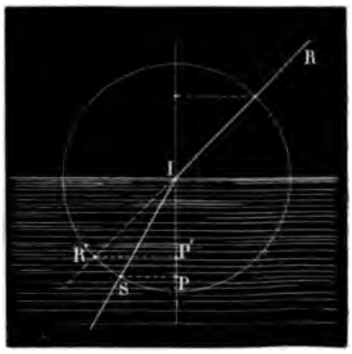


FIG. 197.—Law of sines.

and refraction will have inversed sines, the quotient of which, however, will be always constant.

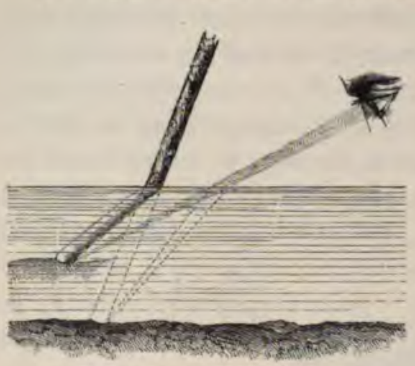


FIG. 198. – Explanation of the bent stick.

These laws account for the phenomena described at the commencement of the chapter. The eye which examines the end of a stick in water sees it by means of the luminous rays which this extremity sends to the surface; which rays are refracted the more as their incidence is more oblique. The phenomenon is therefore the same as if the luminous point were situated at the point of convergence of these rays, and the eye in reality sees the end of the stick in this point. The same effect is produced for all intermediate points, and the stick appears bent. The same explanation accounts for the elevation of

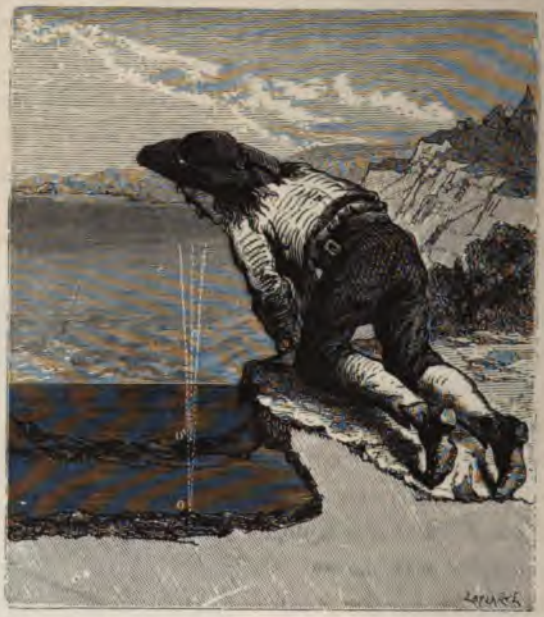


FIG. 199.—Apparent elevation of the bottoms of vessels; explanation.

the bottoms of vessels filled with liquid. Even when we look at the bottom in a perpendicular direction, the effect is produced, because the eye does not receive a single ray, but a bundle of rays, which diverge more on passing through the air, on account of refraction, than through the liquid. The point then appears to rise towards the surface from O in O′ (Fig. 199).

A singular phenomenon called *total reflection* results from the laws of refraction, which may be proved by experiment. Let us imagine a luminous point placed in water, at the bottom of a vessel. This point sends out rays of light in every possible direction at the surface of separation of the air and water. Now, do all these rays emerge? We shall see that this is impossible, and that there is a certain angle, variable with the nature of the medium, beyond which the luminous ray cannot penetrate into a less refractive medium. Indeed, since the angle of refraction is greater than the angle of incidence, a moment will arrive when the first angle having become a right angle, the angle of incidence O I N′ is still less than a right angle. The refracted ray no longer emerges; it grazes the horizontal surface of the liquid. Beyond this, the angle of incidence always increasing, the angle of refraction would become greater than a right angle. In this case the ray returns into the liquid, and is reflected, according to known laws, to the inner surface of separation. As in the least incidences the emergence is not complete, and there is a partial reflection of the rays, so when the emergence is *nil*, there is said to be a total reflection. All the luminous rays which, coming from O, cut the surface of separation

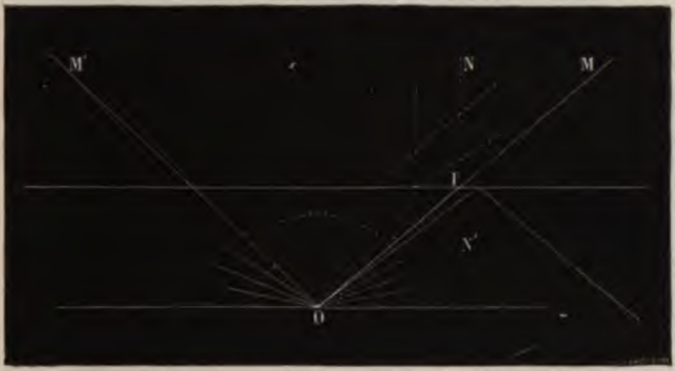


FIG. 200.—Total reflection. Limiting angle.

of the two media, are thus divided into two portions: the fi containing those which emerge, forms the cone of refracted rays; second is composed of all the rays which cannot emerge, and wh are therefore reflected back into the interior of the most refract medium.

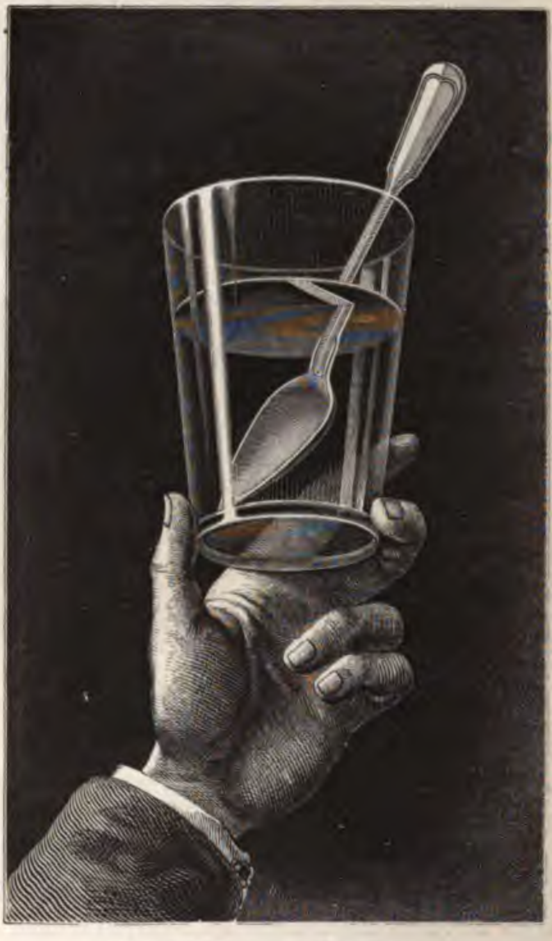


FIG. 201.—Phenomenon of total reflection.

We name *the limiting angle* that beyond which the total reflec commences. This angle is about $48\frac{1}{2}°$ for rays which are refra from water into air, while it is only 41° from glass to air.

A very simple experiment proves the phenomenon of t reflection, and, at the same time, shows that reflection thus obtained exceeds in brightness all those which are obtained directly; for example, at the surface of mercury or polished metals. A glass of water is held in such a position that the surface of the liquid is above the eye (Fig. 201). If we look obliquely from below at this surface, it appears brighter than polished silver, and seems to possess a metallic brilliancy. The upper part of an object plunged in the water is seen reflected as in a mirror.

A diver, immersed in perfectly still water, and having his eyes directed towards the surface of the liquid, would witness singular phenomena. Refraction will cause him to see, in a circle of about 97 degrees in diameter, all the objects situated above the horizon, more distorted and narrowed, especially in height, as they approach the sensible horizon. "Beyond this limit, the bottom of the water and the submerged objects would be reflected, and would be pictured to the sight as distinctly as by direct vision. Moreover, the circular space of which we have spoken would appear to be surrounded by a perpetual rainbow, coloured slightly, but with much delicacy." (Sir J. Herschel.)

The phenomenon of total reflection also explains how it happens that an isosceles and rectangular glass prism, fitted to the opening of the shutter of a camera obscura, intercepts all the light coming from the outside, and leaves the room in the most complete obscurity. The rays which enter the prism by its perpendicular side do not suffer refraction, but when they have arrived at the oblique surface, the angle of incidence is 45 degrees; that is to say, greater than the limiting angle. The total reflection takes place, and there is no emergence. The rays which alone could enter would be due to oblique incidences, which are prevented by the tube containing the prism.

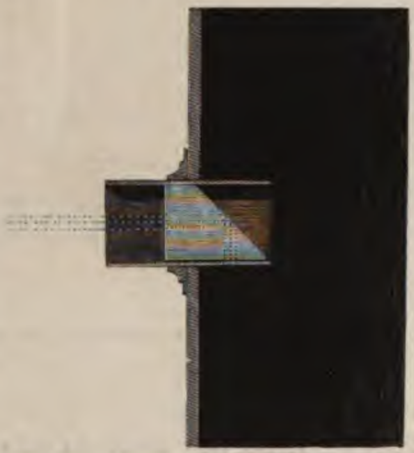


FIG. 202.—Phenomenon of total reflection, in the shutter of a camera obscura.

The phenomenon of refraction occurs whenever a ray passes obliquely from one medium into another, provided that they differ in nature and density. It is evident, then, that the luminous rays emanating from planets, the sun, the moon, and fixed stars, which, after having travelled through the celestial space, have to traverse the strata of our atmosphere before reaching the eye, are subjected to refraction. Hence then we do not see these bodies in the direction of the right lines which really join each of them to the position which we occupy on the surface of the earth. There is no exception except for those situated at the zenith of each horizon. Atmospheric refraction depends on the angular height of the body observed above the horizon; it depends, likewise, on the law which regulates the decrease of density of the strata of air constituting the atmosphere. As we have at present very uncertain data concerning this law, it would be very difficult to measure directly the deviations which correspond to the various heights of bodies. Happily, astronomy has come to the help of physics. As the angular distance of a star from the celestial pole remains invariable, it follows that, whatever may be the height to which the diurnal movement brings it above the horizon, the differences, which observation indicates between the distances obtained from the greatest elevation and at the horizon, can only proceed from atmospheric refraction. Hence it is possible to construct a table of astronomical refractions from the horizon to the zenith.

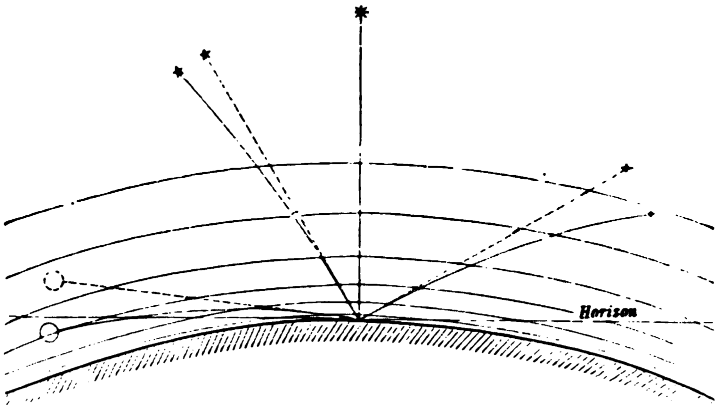


FIG. 203.—Atmospheric refraction. The effect on the rising and setting of stars.

At the horizon the refraction is nearly 34′. As the diameters of the sun and moon have a less value, it follows that at sea, when no object hides the horizon, the disc of the sun at sunrise would appear entirely above the liquid surface before the top of that luminary had emerged above the real horizon. The day is thus found lengthened in the morning by refraction, and the same thing happens in the evening with the setting of the sun.

The same phenomenon accounts for the peculiarity observed in many eclipses of the moon, that the latter body is seen eclipsed, while the sun is still visible above the eastern horizon. Lastly, it is atmospheric refraction which, in total eclipses of the moon, allows a certain number of solar rays to reach our satellite, preventing its disc from being completely invisible. This disc, then, presents a very marked reddish colour, similar to the tint of the atmosphere at sunset.

CHAPTER VI.

REFRACTION OF LIGHT.—PRISMS AND LENSES.

Transparent plates with parallel faces; deviation of luminous rays—Multiple images in a silvered mirror—Prisms—Phenomena of refraction in prisms—Converging and diverging lenses—Real and virtual foci of converging lenses; real and virtual images—Foci and images of diverging lenses—Dark chamber—Megascope—Magic lantern and phantascope—Solar microscope.

WHEN a luminous point is examined through a plate of transparent substance, glass for instance, the two plane faces of which are parallel, if the eye and the luminous point are on the same perpendicular in regard to the plate, the luminous point is seen in the direction where it would be seen without the interposition of a refractive medium. This is the case because there is no refraction for normal rays, that is for rays falling perpendicularly on a surface.

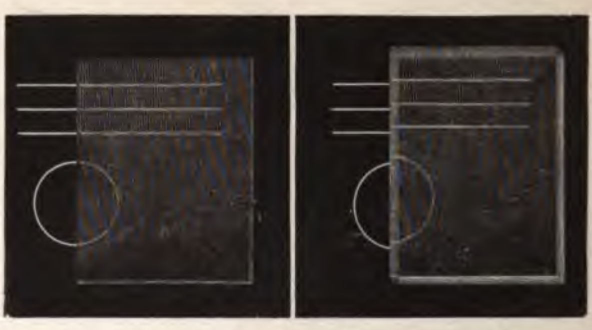


FIG. 204.—Normal View. FIG. 205.—Oblique View.
Deviation due to refraction through plates with parallel faces.

But the same result does not take place in the case of an oblique incidence, for then the position of the luminous point is altered, and the deviation may be rendered evident by a very simple experiment. Take a sheet of glass, place it upon a piece of paper, upon which straight and curved lines have been drawn in such a manner that the glass only covers one part of the lines. If we look at it perpendicularly, we shall observe that the lines seen through the glass are a continuation of the lines seen by direct vision. If we look at it obliquely, we shall notice a deviation, a solution of continuity, the more marked as the incidence of the luminous rays is more oblique. This deviation is due to refraction, and it increases with the thickness of the plates.

It evidently follows from this that transparent plates, such as window-panes, and the glass used to cover engravings, distort the images; but this defect is scarcely perceptible, and is rarely remarked.

When we speak of deviation, we mean lateral displacement, for the luminous ray which traverses one or more plates with parallel faces, preserves after its emergence a direction parallel to that of the incident ray, as shown in Fig. 206. This property is a consequence of the parallelism of the normals to the points of incidence and emergence as well as of the laws of refraction for two media, the refractive power of which is known. Experiment proves that the rays are always parallel when they emerge, after having traversed any number of plates, even when these plates are not formed of the same substances and when they are not all parallel to each other; and theory foresaw this result. Again the same result is produced when plates of different substances are so arranged. The lateral displacement depends, in every case, on the refractive power of the substances and the thickness of the plates.

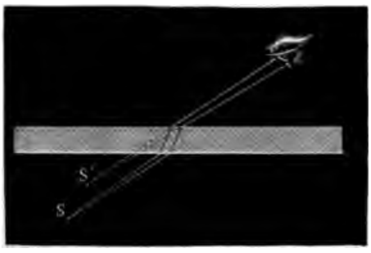


FIG. 206.—Path of a luminous pencil.

If we place a candle in front of a silvered mirror, and hold it obliquely so as to examine the image, we shall perceive, before the bright image formed on the inner silvered face, a more feeble image proceeding from the outer face of the glass, and also a series of images still less brilliant behind the first. These latter images are due to the rays which, after being refracted the first time in the thickness of the plate, are partially reflected silvered surface and by the interior surface of the external

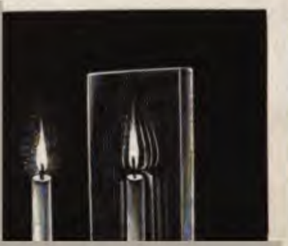


FIG. 207.—Multiple images produced by refraction in plates with parallel faces.

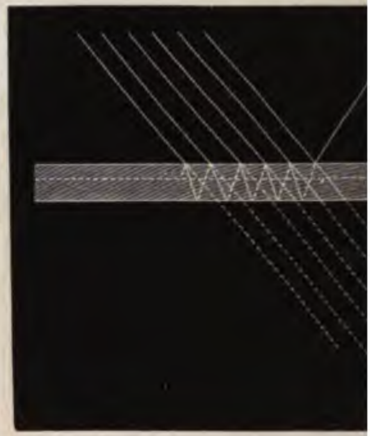


FIG. 208.—Path of the rays which give pla multiple images of plates with parallel

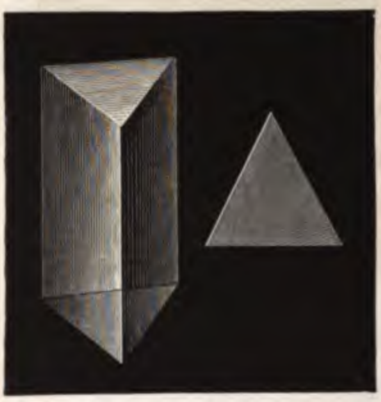


FIG. 209.—Geometrical form of the prism.

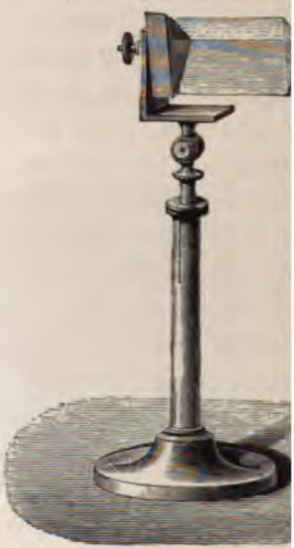


FIG. 210.—Prism mounted on a

of the mirror. Fig. 208, which gives the successive path o rays, accounts for the phenomenon we have just described.

We will now examine the phenomena which depend on the refraction of light, when it traverses a refractive medium, the plane faces of which are not parallel, that is to say, in prisms.

Fig. 209 shows both in perspective and in section the geometrical form of a prism as used in optics. For the convenience of experiment, the prism is mounted on a stand, in such a manner that it can be turned round or inclined at will (Fig. 210).

The effect of a prism on a luminous ray, which enters obliquely at one of its faces, traverses the prism, and emerges from the other face, is to deviate the ray towards the side which constitutes the base. It is sufficient for us to examine Fig. 211, which shows the path of the incident and refracted rays, to prove this: the incident ray S I after the first refraction takes the path I E in the prism, is again refracted on emerging from the prism, and finally issues in the direction E R. This is confirmed by observation, for if we examine an object through a prism, by placing its edge in a horizontal position, the image appears raised up, if the base is below; and it is lowered, if the base occupies the reverse position. In fact, the eye sees the luminous points in the direction of the rays which leave the prism. If, as we have just seen, the bundle of rays diverges and approaches the base of the prism, their convergence will take place towards the summit, and the eye will see the point raised or lowered according as the base is above or below the opposite angle.

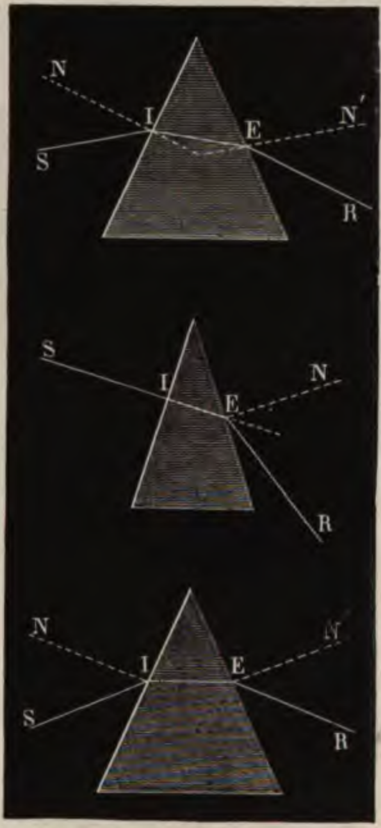


Fig. 211.—Deviation of luminous rays by prisms.

The *deviation* of the rays increases with the angle of the prism, when the angle of incidence of the rays remains the same. For the same prism, in proportion as the incident ray approaches the normal the angle of emergence increases, and there is a direction in which the rays attain the limiting angle of total reflection, when there is no more emergence. This depends, however, on the substance of which the prism is composed.

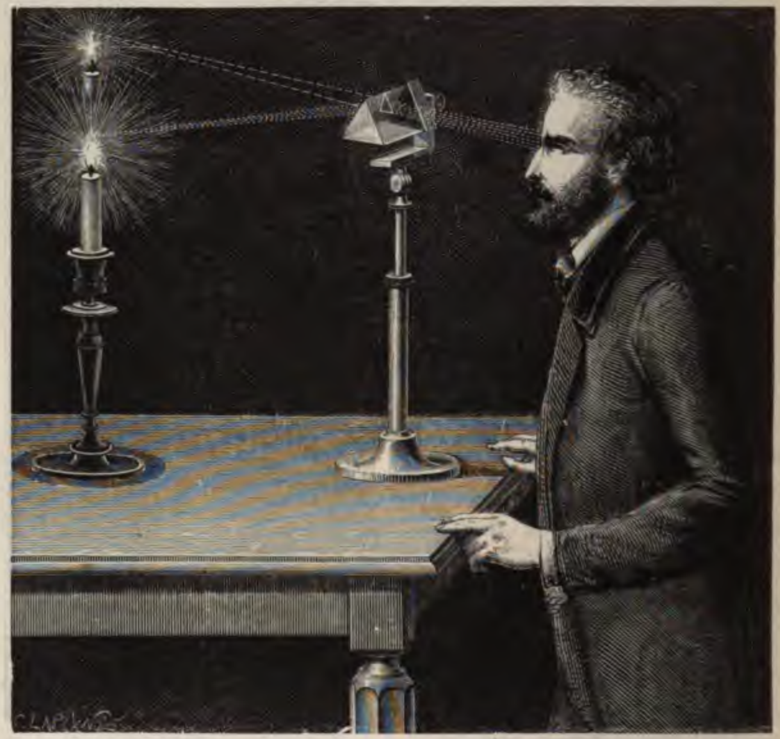


FIG. 212.—Images of objects seen through prisms.

In the case of a glass prism of 45°, all rays which fall below the normal towards the base cannot emerge; but those which fall towards the summit become emergent rays. If the angle of the prism is double, that is to say, a right angle, no luminous ray, whatever may be its incidence, can emerge out of the prism; so that such a prism, with a blackened base, if placed at the opening of a shutter in a dark room in a transverse position, and so as to close the opening, would allow no luminous ray to enter.

We shall presently describe other phenomena of great interest, obtained by the aid of prisms, through which rays from different light-sources pass; phenomena which show that white light is formed of a multitude of rays of different colours, each being refracted in a different degree. This is called the decomposition or *dispersion* of light. But having now dealt with *deviation*, we must first consider the path of a ray when it traverses transparent media with curved surfaces.

LENSES.

If we construct of glass, or of other transparent substance, a disc with two convex faces, that is to say, two segments of a sphere with their bases in conjunction, we have what is called a lens. The name is taken from the resemblance which exists between the form of such a mass and that of the well-known vegetable—the lentil.

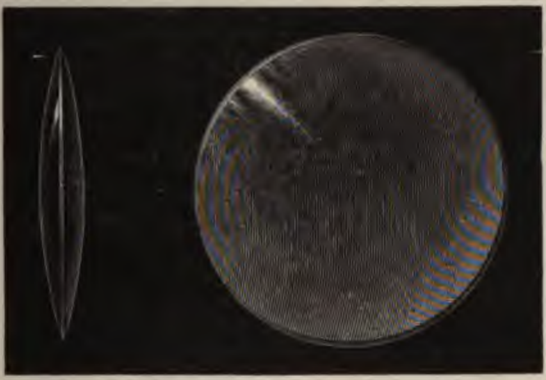


FIG. 213.—Magnifying glass or lens with convex surfaces, side and front view.

There are various kinds of lenses; that which we are about to describe, which forms the instrument called the magnifying glass, is used by almost every one, as for instance naturalists, engravers, watchmakers, &c., who wish to enlarge the smallest parts of objects so as to be able to see them in detail.

There can be no doubt that glass lenses and their magnifying effects have been known for ages. Analogous objects have been found in the ruins of Nineveh, Pompeii, and Herculaneum. Spectacles have been used in Europe since the beginning of the fourteenth century. But it is only for the last three hundred years that the knowledge of the laws of refraction has enabled opticians to construct and to combine lenses, so as to obtain various desired effects with accuracy.

Physicists have extended the name of lenses to all transparent masses, terminated, at least on one side, by curved, spherical, or cylindrical surfaces, even when these surfaces are concave instead of convex, as in the magnifying-glass. More often, and indeed whenever the contrary is not stated, the surfaces of lenses are both spherical; or one may be plane, and the other spherical. We shall thus regard a lens throughout this work. All lenses may be conveniently grouped in two classes, according to the path which the light which traverses them follows. Some, as in the magnifying-glass, are converging, that is to say, the luminous rays after their passage through the lens are drawn together; others are diverging, because, on the other hand, the rays become more distant from each other, or diverge either on entering, or issuing from, the refractive medium of which they are formed. These can be very simply distinguished at first sight, for converging lenses are always thicker at the centre than at the circumference, while diverging lenses are thinner at the centre than at the circumference.

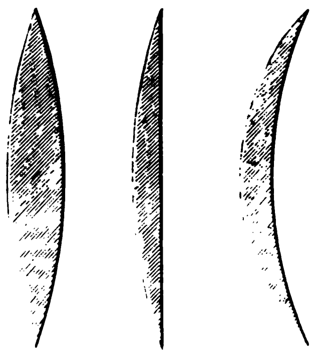


FIG. 214.—Converging lenses.—Bi-convex lens; plano-convex lens; converging meniscus.

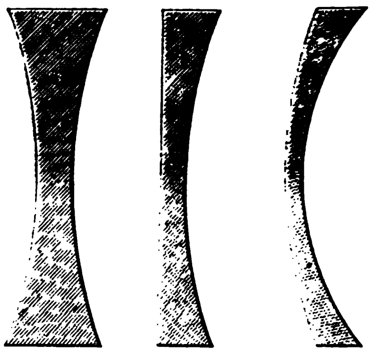


FIG. 215.—Diverging lenses.—Bi-concave lens; plano-concave lens; diverging meniscus.

The type of converging lenses is the magnifying glass or bi-convex lens, the two surfaces of which, generally of the same curve, are convex. Next we have the plano-convex lens, one surface of which is plane, the other convex. Lastly, the third converging lens is the converging *meniscus,* one surface being concave and the other, a more decided curve, is rounded or convex. Fig. 211 gives the form of each of these lenses seen edgewise, supposing the section to be made in the direction of diameter.

The type of diverging lenses is the bi-concave, formed of two concave surfaces. Next, the plano-concave lens, one surface being concave, the other plane; and the diverging meniscus, the two surfaces of which are, one convex, the other concave, this latter having a sharp curve.

We may also state that the principal axis of a lens is the right line which passes through the centres of the spheres to which their surfaces belong, or, if one of these is plane, the line which, from the centre of the curved surface, falls perpendicularly on the plane surface. In converging lenses, the axis passes through the lens at its greatest thickness; while with divergent lenses it is the reverse.

Without the aid of experiment, the known laws of refraction indicate to us that a ray of light which is propagated in the direction of the axis, will traverse the lens without deviation and will continue its path in the line of the axis, exactly as if it normally traversed a plate with parallel faces.

There are other lines which have an analogous property, and which are called *secondary axes.* They are those lines which cut the principal axis at the middle of the maximum or minimum thickness: I O I′ (Fig. 216) is a secondary axis in each of the lenses represented. When a luminous ray N I on entering follows the direction of one of these lines, it emerges in a direction N′ I′ parallel to that of the incident ray; and as the thicknesses of lenses are generally very small, it may be said that the incident ray and the

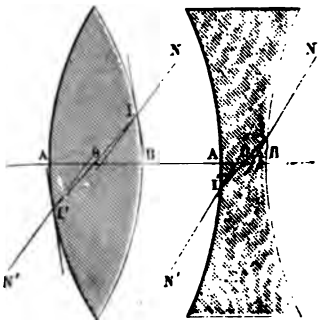


FIG. 216.—Secondary axes of lenses. Optical centre.

emergent ray pass in the direction of the secondary axis. The *optical centre* of a lens is the point where the principal axis and the secondary axes meet. The optical centre is still in the interior, if the two surfaces have not the same curvature, but it is no longer situated at an equal distance from the two surfaces. For plano-convex and plano-concave lenses, the optical centre is on the curved surface; in the converging and diverging meniscus lenses, it is outside the lens.

These definitions being understood, let us now examine the path of light through a bi-convex lens. If we place it facing the sun, so that its principal axis is parallel to the rays of light issuing from that luminary, and then receive the light which emerges from the lens on a screen placed a short distance on the other side of it, we shall perceive on the screen a luminous circle, the clearness and dimensions of which depend on the distance of the screen from the lens. When we move it further away or nearer to the screen, we find a position when this brightness will be at its maximum, and the clearness of the circular image will be greatest and its magnitude the least. This would be a mathematical point, if the source of light were itself a point. This point, to which the parallel rays converge after their refraction to the principal axis, is called the *principal focus* of the lens. The distance F A from the focus to the lens, which is called the principal focal distance, depends both on the substance of which the lens is made and on the curvature of its surfaces. The greater the curvature, the less is the focal distance, which is expressed by saying, that the lens is of short focus.

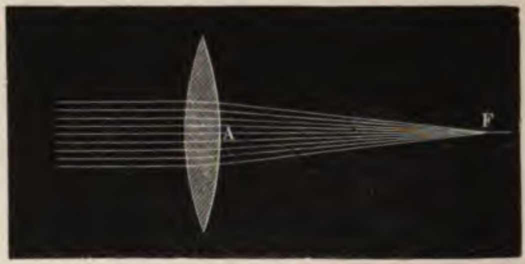


FIG. 217.—Path of rays parallel to the axis. Principal focus.

If a lens is placed in the opening of a dark room, the convergent path of the sunlight can be traced in the air, because the luminous cone renders evident the particles of dust which fly about in the room.

The convergence of luminous rays produced by bi-convex lenses readily explains the path of refracted light through a prism. The effect produced by this latter medium is to cause the luminous ray to approach the base of the prism. Now, a bi-convex lens may be considered as an assemblage of superposed prisms, the angle being more acute as it approaches the principal axis, while the deviation is greater as the angle is more obtuse. Fig. 218 shows this convergence, and experiment agrees with theory in showing that the point of meeting is on the principal axis, provided that the rays are very near the axis.

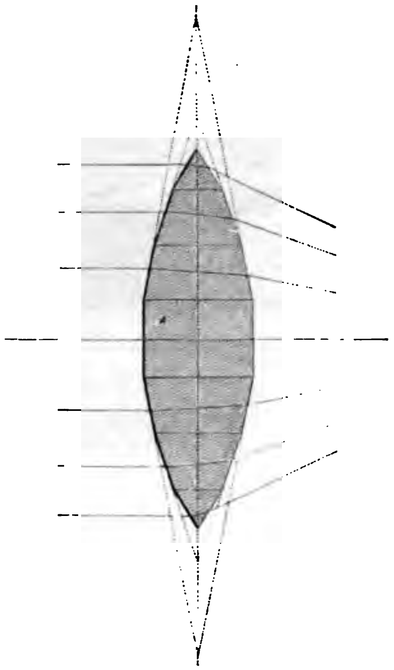


FIG. 218.—The lens may be considered as an assemblage of prisms.

Let us examine the different circumstances which result, when the luminous point S (Fig. 219) is near the lens, and in the principal axis. The explanation is the same, when the luminous rays, instead of starting from a point situated at an infinite distance, proceed from a light situated on the axis at a finite distance. Only, in this case, the focus does not coincide with the principal focus. As long as this point is on one side of the lens, beyond its focal distance, its focus S is formed on the axis beyond the principal focus, and the more it approaches, the more distant is the focus. If it does not happen to be more distant from the lens than double the focal distance, the corresponding focus is precisely at the same distance. If it again approaches the lens, the focus continues to recede, until the luminous point, attaining the focal distance itself, its focus as if they emanated from this focus, and the impression they receive is that of the image of the luminous point.

The nearer the object approaches the lens, the more does the image itself approach it; and when the object comes into contact with the transparent surface, the image arrives there at the same time.

These results can be proved both by calculation and experiment. Let us examine, experimentally, images both real and virtual, which are formed at the focus of a bi-convex lens or, in general, of a convergent lens, when it is placed opposite a luminous object.

We have already seen how the image of an object whose distance may be considered as infinite, and which sends to the lens a beam of parallel rays, is formed; it is thus that the sun produces an image in the principal focus of the lens.

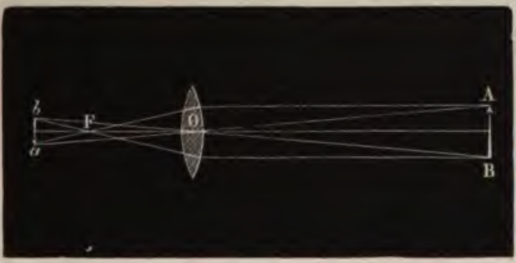


FIG. 221.—Real image, inverted and smaller than the object.

If the object A B is at a finite distance, more than double of the principal focal distance, it will be real, inverted, and smaller than the object.

This may be proved by receiving the image of a lighted candle on a screen which we can move nearer or further away from a lens, until we obtain a perfectly clear image. As the distance of the candle diminishes, the image, which is always real, will recede and become larger, until it is of precisely the same size as the object itself. If the distances are measured which separate the lens from the screen and from the candle, they are found to be equal, and each is double that of the principal focal distance. As the candle continues to approach the lens, the real image enlarges and recedes; and it is then larger than the object (see Figs. 222 and 223). We must increase the distance of the screen if we wish for clearness, but it will be seen that the brightness diminishes, which is explained by the dispersion of the luminous rays proceeding from the lens on a surface which increases quicker than the quantity of light received.

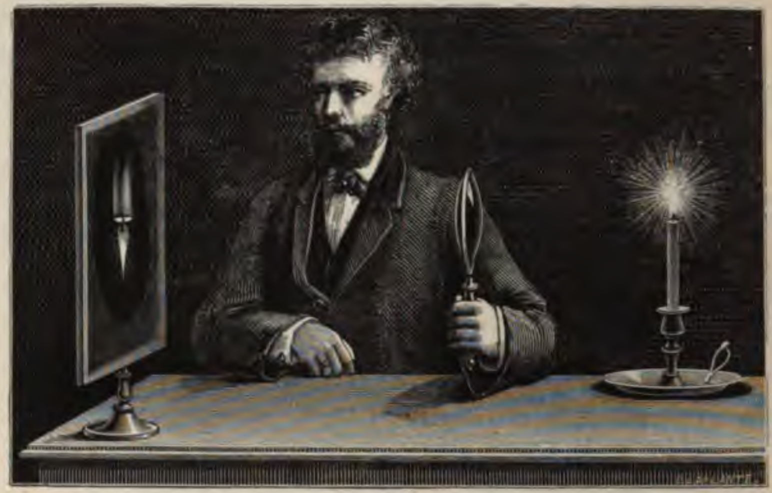


FIG. 222.—Real image, inverted and larger than the object.

When the candle has arrived at the focal distance, the image disappears; and this is easily explained, for as the rays issue parallel to the axis, there can no longer be convergence. Thus far, the image has always been real; in other words, it has always been possible to receive it on a screen; its existence has been independent of the observer. This will no longer be the case if we continue to

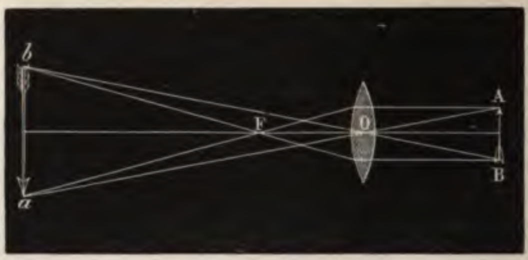


FIG. 223.—Image of an object situated at a distance from the lens greater than the principal focal distance, and less than double that distance.

advance the candle or other luminous object towards the lens; for then the screen placed at any distance will only give diffused light. If, however, instead and in place of the screen, we substitute our eyes, we shall see through the lens an image of the candle, no longer inverted, but erect and magnified. How then does it happen that the eye receives the sensation of an image which is not then real?

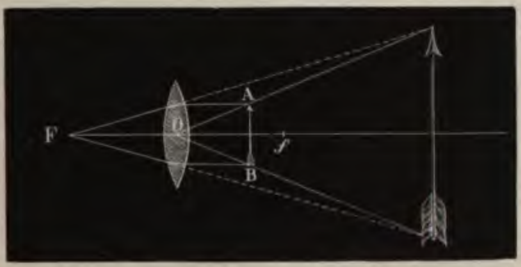


FIG. 224.—Erect and virtual images of an object placed between the principal focus and the lens.

The luminous rays which each of the points of the object sends to the lens issue from the refractive medium in a divergent form. The eye which receives them undergoes the same sensation as if it were acted upon by rays emanating directly from luminous points situated on the other side of the lens, but at a much greater distance than the object to which they belong. Hence, the increase of apparent dimensions; and also, the direction of the image, which, becoming virtual, ceases to be inverted (Fig. 224). In this instance, in proportion as the object approaches the lens the image diminishes, until it touches one of the surfaces of the lens, when the image becomes sensibly equal to the object itself. These are the images produced by converging lenses.

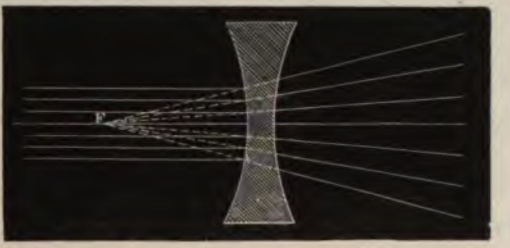


FIG. 225.—Principal virtual focus of diverging lenses.

Diverging lenses have no real focus. For example, in the case of a bundle of rays parallel to the axis—which occurs when the luminous point is situated on the axis at an infinite distance—in issuing from the lens the rays diverge; their point of intersection is situated on the axis in front of the lens, and is called the principal focus, a focus which is no longer real but virtual. The eye which receives the divergent beam emerging from the lens experiences the same sensation as if there was actually a luminous point at the focus.

Diverging lenses do not produce a real image, because the luminous rays, on emerging from a refractive medium, are separated from each other, and have no effective point of union. But if we apply to them the treatment before adopted in the case of the erect and virtual image given by a converging lens, we perceive that the images of diverging lenses are likewise virtual and erect. But there is this difference, viz. that their apparent dimensions are always less than those of the objects which they represent. Fig. 226 indicates the cause of this, and enables us to understand why images, which become smaller as the object is more distant, attain the size of the object itself, when this latter touches the lens.

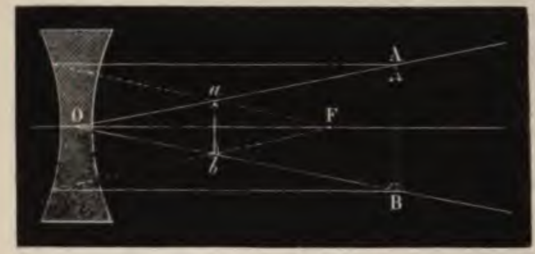


FIG. 226.—Erect virtual images smaller than the object in a bi-concave lens.

Both converging and diverging lenses are used in the construction of numerous optical instruments, in astronomical telescopes, microscopes, lighthouses, &c.

We shall describe the most important of these in the volume which treats of the "Application of Physics," and shall see how wonderfully science is concerned in these operations. We shall here confine ourselves to the construction of the most simple instruments, in which real images are caused to produce various optical effects; these are principally the camera obscura, the megascope, the magic lantern, the solar microscope, and the phantascope.

Why

In considering the propagation of light in right lines, we have seen that if a small hole is made in the shutter of a perfectly dark room the image of exterior objects is thrown on the screen. This inverted image is only distinct in the case of distant objects. To obviate this inconvenience and to give brightness to the images, Porta conceived the idea of receiving the light on a spherical concave mirror, which reflects both the rays and the image on the screen. But he also obtained effects much more remarkable, by placing a converging lens in the hole of a shutter, when the images of outer objects were found to be given with distinctness on a screen, the distance of which from the opening of the shutter varied with the distance of the objects themselves. It is easy to determine this distance by moving the screen backwards and forwards. Designers employ this dark chamber, in order to trace on paper the outlines of a landscape they may wish to produce. They make use of it in the form indicated in Fig. 227. Instead of a lens, they use a prism (Fig. 228), the side of

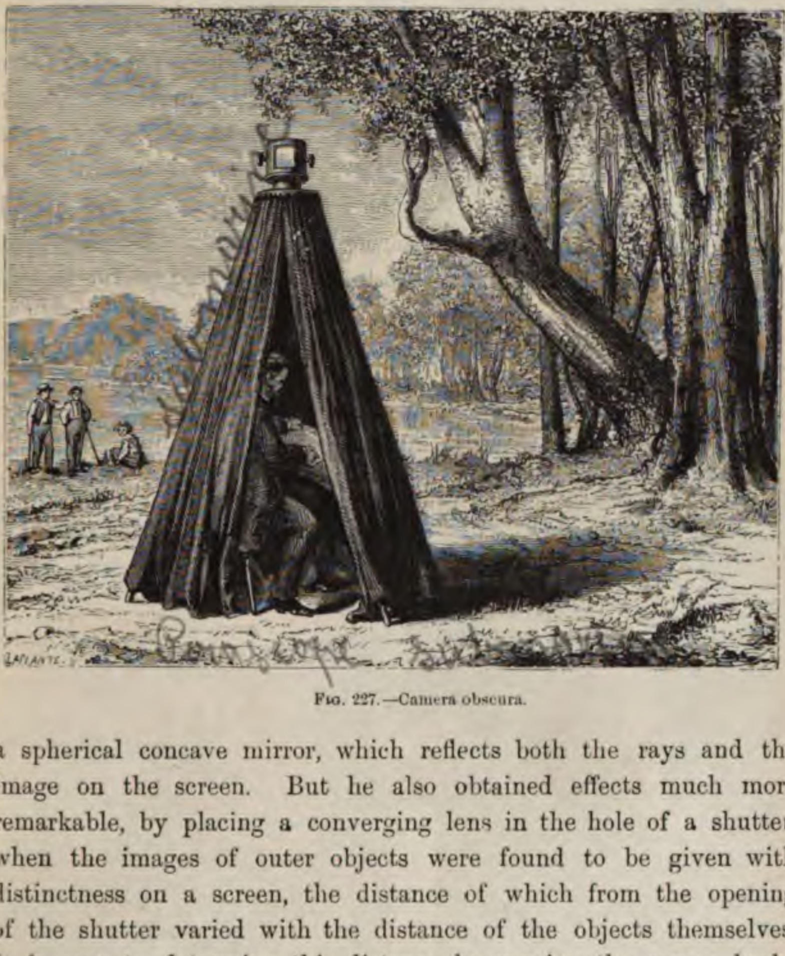


FIG. 227.—Camera obscura.

which, turned towards the object, is convex, and, by total reflection from its plane surface, which is inclined at 45°, it projects the beam of light upon the table, on which is placed white paper. The image thus formed is perfectly clear, and the draughtsman has nothing to do but follow the outlines in pencil. This modification of the camera obscura is due to M. C. Chevalier, the optician.

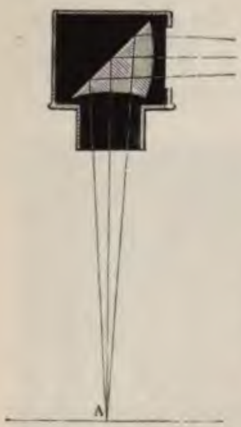


FIG. 228.—Lens-prism of the camera obscura.

The megascope is a dark chamber used for the purpose of reproducing an object on a large scale, such as a statuette, or picture. Fig. 229 will save us a more detailed description. We may remark that, as the brightness of the object is enfeebled by the dispersion due to enlargement, a mirror is used to project the sun's rays on the object, and to obtain a sufficiently intense light.

The magic lantern is a megascope in which the object is illuminated by means of a reflecting lamp. By the use of this apparatus, the enlarged images of pictures painted on glass with transparent colours are projected on a screen. The tube through

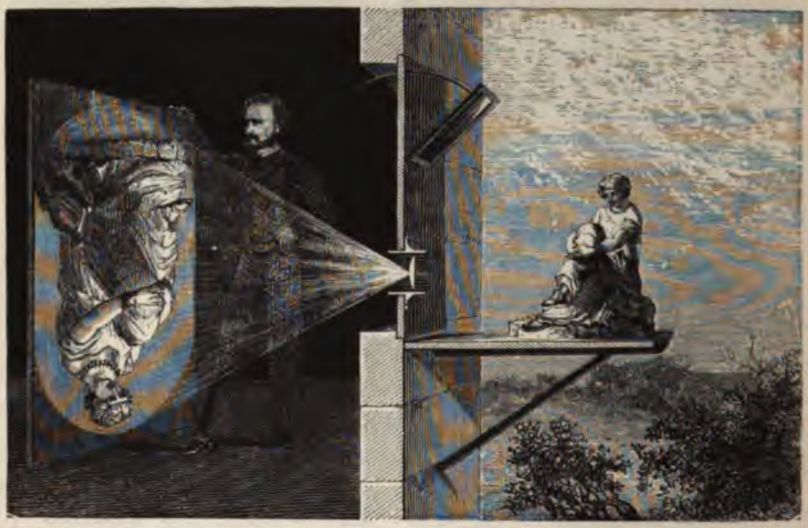


FIG. 229.—Megascope.

which the inverted drawings are placed encloses a system of two lenses, one plano-convex, the other bi-convex, which produce an erect image on a screen in front of the instrument. By using Drummond's light to illuminate the objects, far more brilliant images are obtained; and, by moving the screen further away and bringing the lenses nearer together, the images can be greatly enlarged.

Towards the end of the last century, a Belgian physicist, Robertson, obtained an extraordinary success by exhibiting, in public, apparitions of phantoms, which, in the profound darkness surrounding the spectators, appeared to gradually advance into the middle of the room, and to increase in size. This was done by means of an apparatus called a phantascope, analogous to the magic lantern, that is to say, consisting of a box, containing a reflecting lamp, and furnished with a tube having the same system of two lenses to project the image of a drawing on a screen placed in front of the instrument. But in this case the lantern is supported by a moving table, one of the feet of which has a pulley communicating its movement to the lenses through the intervention of an eccentric and lever. When the table moves further from the screen, the plano-convex lens approaches the convex lens, the image increases, and the illusion is produced in a much more complete manner than by the aid of a moveable diaphragm; the light which the image receives varying in proportion to its size. Robertson, who owed the secret of this invention to an artist named Waldech, was careful to exclude all extraneous light; and, to avoid any noise produced by the apparatus, the wheels were covered with wool. He further augmented the illusion by imitating the noise of thunder, rain, the cries of animals, &c.

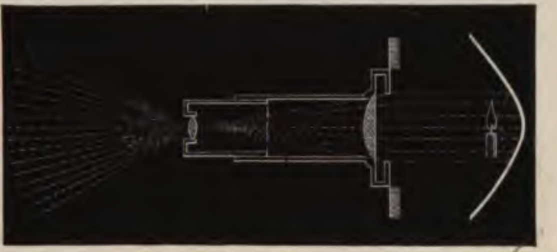


FIG. 230.—Magic lantern.

In Fig. 231, a double lantern is shown, from which, besides the image of the spectre or any other fantastic personage, that of a landscape in harmony with the scene produced, can be projected on the screen.

The same double apparatus also gives polyoramic views; that is, effects of varied landscapes, a succession of day and night, calm sea and tempest, &c. Each lantern is disposed in such a manner as to project each double view at the same place on the screen. One of them is at first closed, and a landscape illuminated by the sun is seen; by degrees the light diminishes, twilight comes, then night, and imperceptibly the second view is substituted for the first. Children, and even grown persons, often admire these pictures and effects of light; the principle interests us here, rather than the details of the mechanism.

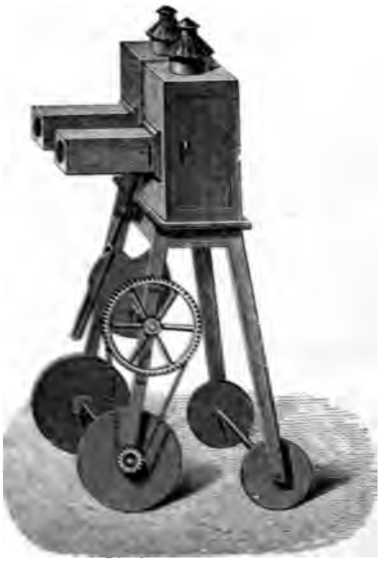


Fig. 231.—Phantascope.

We shall only insist on this point, viz. that the dark chamber, megascopes, magic lanterns, and phantascopes are all based on the formation of real images, by means of converging lenses.

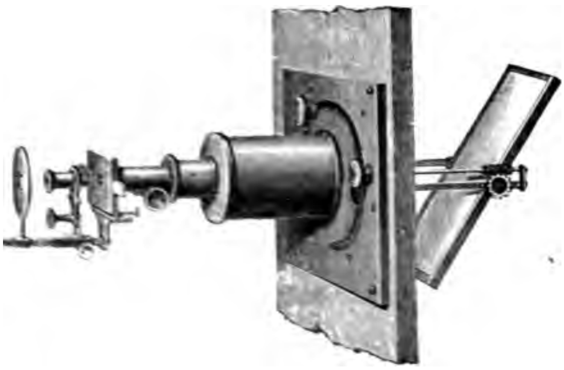


Fig. 232.—Solar microscope; complete.

Such is also the principle of the solar microscope, which is not less interesting than the instruments before described, and certainly more useful for the study and teaching of science.

The solar microscope is used to project the image of a small object, in a considerably enlarged form on a screen. It is a megascope with the advantage of easy use, and of showing the enlarged object to a large number of spectators. To this end, the object is placed a little beyond the principal focus of a lens of short focus. The enlargement is more considerable as the distance of the object from the focus decreases. But the image will be formed at a much greater distance from the lens; and, the greater the magnifying power, the more will the light be diffused, and consequently enfeebled; hence the necessity of illuminating the object as brightly as possible, so that the image may retain a sufficient degree of distinctness. This is why either the rays of the sun, or those of a very intense source of light, such as the electric light, are used. A mirror reflects and projects the rays of light on a lens of large aperture, which causes them to converge for the first time; a second lens concentrates the rays still more; and at the focus the object, the details of which we desire to examine, is placed. Figures 232 and 233 represent the solar microscope and its internal construction. The gas microscope is that in which Drummond's light is used to illuminate the object; and the photo-electrical one that in which the brilliant voltaic arc supplants the solar rays.

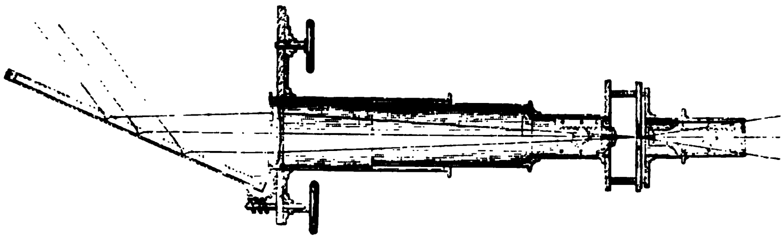


FIG. 233.—Section of the solar microscope.

Nothing is more curious than to see the magnified images of the various organs of the smallest animals; the infusoria which live in a drop of fermenting liquid; the decomposition of water into gaseous globules of oxygen and hydrogen; the crystallization of salts; and the structure of animal and vegetable tissue.

CHAPTER VII.

COLOURS: THE COLOURS IN LIGHT SOURCES, AND IN NON-LUMINOUS BODIES—DISPERSION OF COLOURED RAYS.

White colour of the sun's light—Decomposition of white light into seven simple colours; solar spectrum—Recomposition of white light by the mixture of the coloured rays of the spectrum—Newton's experiment; unequal refrangibility of simple rays—Colours of non-luminous bodies.

THE light which physicists take as a type of all others as regards colour is that of the sun. That the light of the sun is white may be proved by a very simple experiment. If, in the interior of a dark room, the solar light, after passing through a hole in the shutter, is received directly on a piece of white paper, the image of the sun on the paper will be found to be a round white spot. If this experiment were not made in a dark room it would be inconclusive, because the paper would receive, in addition to the solar rays, rays reflected from the surface of other bodies differently coloured.

But this white light is not simple. It is composed of a multitude of colours or tints, which are themselves simple colours. This has been proved beyond doubt by a series of experiments which have been made under diverse conditions, and which are principally due to Newton. We will indicate the most striking of these.

If we place in the path of the solar rays, after their passage through the round hole of the shutter of a dark room, a triangular flint-glass prism in such a manner that its edges are placed horizontally (Fig. 234), and that the beam enters it obliquely by one of its surfaces, we shall see on the screen, at a certain distance above the point where the spot of light appeared before the interposition of the prism, a prolonged luminous band, formed of a series of extremely bright colours; this band is called the solar spectrum. The following is the order in which the colours succeed each other when the prism has its base upwards; the order is the reverse when the base is turned downwards. At the lower extremity of the spectrum is a bright, full red, to which succeeds an orange tint, and this passes by imperceptible gradations into a magnificent straw-yellow. Then comes a green of remarkable purity and intensity; then a greenish blue tint; and then a decided blue colour, which becomes eventually indigo. After the indigo succeeds violet; the palest shade of which ends the spectrum.

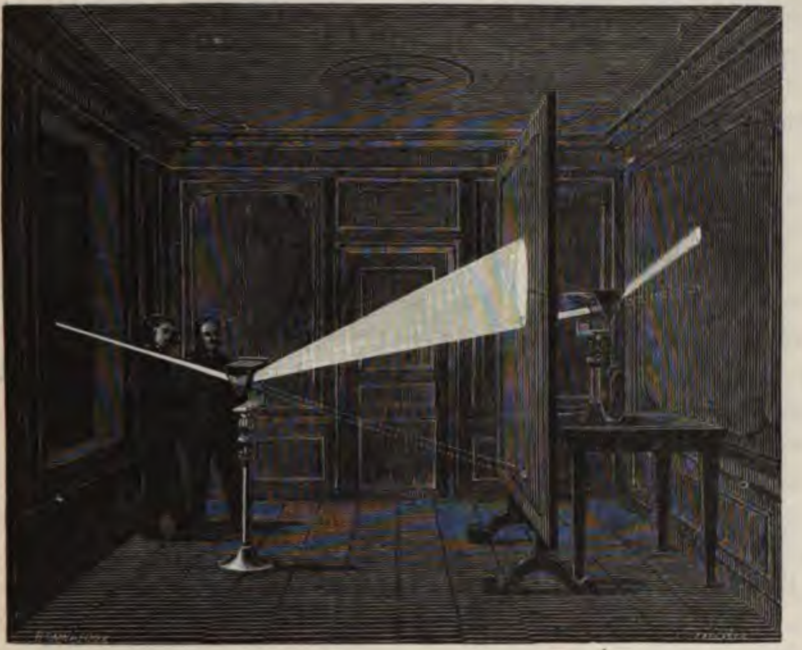


FIG. 234.—Decomposition of light by the prism. Unequal refrangibility of the colours of the spectrum.

Plate IV., Fig. 1, shows the series of colours of the solar spectrum as obtained by a prism filled with bi-sulphide of carbon. Thus a ray of white light is, as we have before stated, the reunion of a series of coloured rays, of which we have mentioned only the principal; for, the transition of one colour into another is made in such an imperceptible manner, that there is no abrupt change of colour nor solution of continuity.[1] Such is the phenomenon of the decomposition, or analysis, of white light, which is also called the *dispersion* of the coloured rays.

[1] Except by the very fine black lines, of which we shall speak further on.

The dispersion of light by refraction is manifested to us every day by numerous phenomena, some of which the ancients also observed, but without suspecting the true cause. Precious stones, such as diamonds, emit lights of different colours; and the decomposition of light by one of its facets is not one of the least beauties of this precious substance. The rainbow is a phenomenon due to the same cause, as we shall show when we come to the description of meteors. It is the same with the various colours which tint the clouds and atmospheric strata at the time of sunrise or sunset. Lastly, in glass vessels containing transparent liquids, and in pieces of glass cut as lustres, we see in certain directions iridescent fringes, presenting the colours of the spectrum in all their purity.

A second experiment proves that each of the colours of the spectrum is simple, and that the degree of refrangibility increases from the red to the violet. This experiment consists in allowing a narrow beam of the coloured light to pass through a small hole made in the screen, at the point where the red light falls, for instance; when this is received on a second screen (Fig. 234), it forms a red image at a point which is carefully noticed. If, instead of receiving it directly on this screen, a second prism is interposed, the luminous beam is again deviated to a higher point than before. But the new image is red, like the first, and of the same form if the prism is properly placed; therefore, the red light of the spectrum cannot be decomposed. The same experiment, repeated with other colours, gives analogous results. All the colours of the solar spectrum then are indecomposable or simple; but their refrangibility increases, for it is noticed that the distances between the direct images of the colours on the screen and the image obtained by refraction in the second prism are greater as the colour is nearer the extreme violet of the spectrum.

If, instead of a prism formed of flint-glass, we use prisms of other solid or liquid refractive substances, we obtain spectra more or less brilliant, and more or less elongated; if the prisms are colourless, the spectra are composed of the above colours, arranged in the same order; but their proportions—that is, the spaces occupied by each of them—vary according to the nature of the substance, whilst the order of the colours remains the same. Flint-glass, among solids, gives the most extended spectrum, especially at the violet end, and bi-sulphide of carbon among liquids.

The angle of the prism also influences the length of the spectrum produced, which is greater as the angle is more obtuse. This fact may be easily proved experimentally, by the aid of prisms having various angles, of which we have spoken above. Thus, white light is decomposed by refraction into rays differently coloured, and the colour of each of the rays corresponds to a particular degree of refrangibility.

This is the analysis of light.

But, if such is indeed the composition of light, white light ought to be produced by uniting all the colours of the spectrum in proper proportions.

Various experiments confirm this consequence of the analysis of light. Most of them are due to Newton, who described them in his "Optics," and they are reproduced in the present day with very slight modifications. The most simple experiment of this nature consists in receiving on a converging lens the solar spectrum produced by a prism. On placing a screen of white paper at the focus where the rays of the different colours are brought to a point (it is the conjugate focus of the point whence the rays emerge from the prism) a white image of the sun is seen (Fig. 235). By bringing the screen nearer to the lens, the separated coloured rays again reappear, brighter as the screen is gradually brought nearer the lens. On the other hand, if the screen is moved away from the lens, starting from the

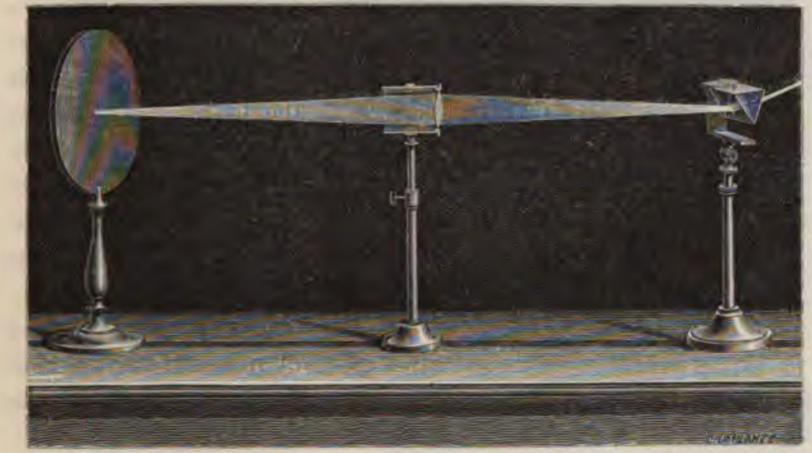


FIG. 235.—Recomposition of light by a lens.

[illegible]

[illegible]

[illegible] Two spectra obtained by means of two different prisms and projected in inverse directions on a screen give white light at the place where the colours are superposed.

If the spectrum given by one prism is observed with a second prism, a position may be found in which the image received by the eye is round and white.

All of these experiments, and others also, are described by Newton with admirable clearness and simplicity. "Hitherto," he says, "I have produced white by mixing the colours produced by prisms. Now, in order to mix the colours of natural bodies, take water slightly thickened by means of soap, and agitate it until it becomes frothy. When this froth has come to a state of rest, if you examine it attentively, you will see various colours on the surface of each bubble of which the froth consists. But if you remove to such a distance that you cannot distinguish the various colours, the froth will appear perfectly white." ("Optics," Book I.)

He also tried to obtain a white tint by the mixture of certain proportions of various coloured powders. Orpiment (orange-yellow sulphide of arsenic) mixed with purple, green, brown, and blue gave him a composition of an ash-coloured grey, which, when exposed to sunlight and compared with a piece of white paper of the same size placed by the side of the mixture and in the shade, appeared of a brilliant white. Newton explains the grey colour of mixtures of this kind by the absorption of light, and it was to obviate this diminution of brightness that he thought it better to illuminate the composition strongly by the solar rays.

Lastly, if a disc, divided into sectors coloured with the principal colours of the spectrum, is caused to revolve rapidly, in proportion as the rotation increases, the individual colours disappear from the eye.

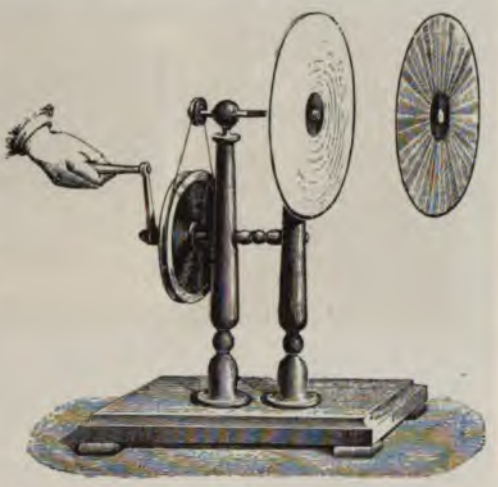


FIG. 237.—Recomposition of white light by a revolving disc.

The disc ultimately assumes a tint which approximates to white according as the true proportion of the different colours has been the better observed. It will be understood that when the successive impressions of the different colours on the retina are confused, in consequence of the rapidity of the movement, it is as if the rays made their impression simultaneously, and the sensation which is produced is that of white. The same experiment can be very simply shown by spinning a top, the surface of which is divided into sectors, in the direction of meridional lines, and painted with the colours of the spectrum. This will appear white or a greyish white in proportion as its rotation is the more rapid, and the colours will gradually reappear as the motion slackens.

The phenomena which we have just described are produced by solar light. But it must not be forgotten that by this term must be understood not only the light due to the rays which arrive directly from the sun but also all light originating from this body: that of clouds, the atmosphere, and the light of the moon and planets. Analysed by means of a prism, these give spectra of very variable brightness, but their composition as regards coloured rays is precisely the same as that of the solar spectrum.

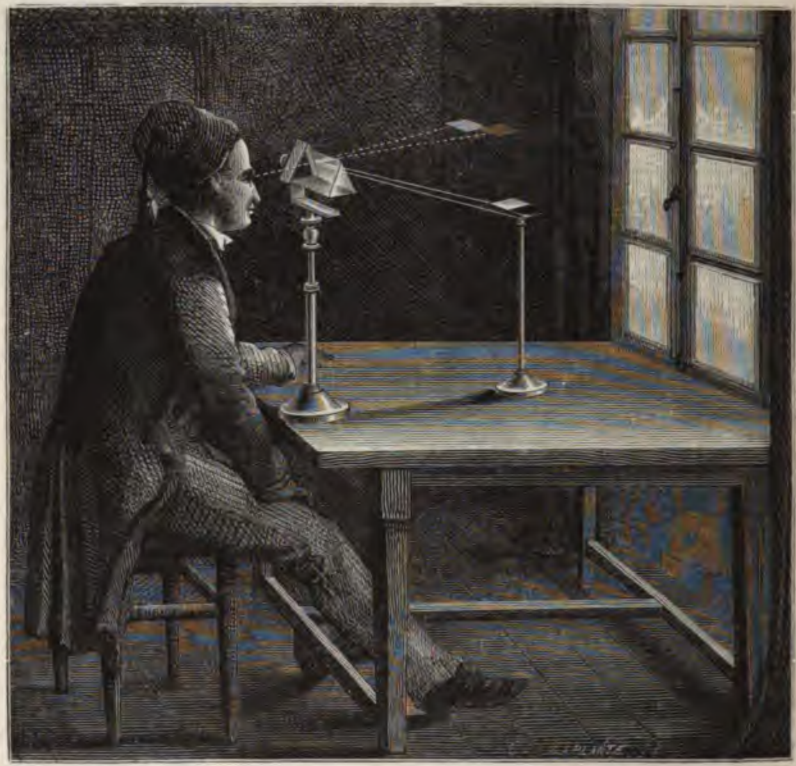


FIG. 238.—Unequal refrangibility of various colours.

Lights proceeding from other sources, stars, artificial flames, the passage of electricity, either in physical apparatus or in storms, all produce spectra, in which the colours are disposed in the same order as the colours of the solar spectrum. But generally speaking the phenomenon is less brilliant, and, as we shall soon see, it happens in some cases that certain colours are not seen, and are found to be replaced by dark lines.

The experiments which serve to show that the different colours of the spectrum give, by their reunion, white light, are as conclusive when we use the coloured rays of the spectrum, as when the colours of illuminated bodies are employed. This is in itself sufficient to prove that these latter colours are, like those of luminous sources, unequally refrangible. But Newton made direct experiments on this difference by examining with a prism a piece of paper, the two halves of which were differently coloured, the one being red, and the other blue. The prism and the paper were placed in front of a window, as shown in Fig. 238, and he noticed that the two halves of the paper appeared unequally deviated, the blue half being lower than the red, so that the paper appeared divided into two parts, the one no longer a continuation of the other; the reverse happened when the angle of the prism was placed in the contrary direction: therefore blue is more refrangible than red.

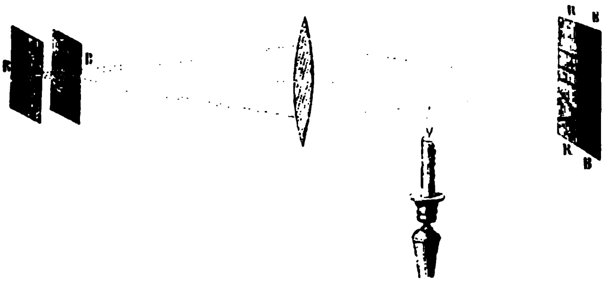


FIG. 239.—Unequal refrangibilities of simple colours. Newton's experiment.

By receiving on a screen of white paper placed behind a lens the images of the same paper illuminated by a candle, Newton likewise discovered that the screen must be placed at different distances to obtain clear images of the blue half and the red.

A black silk cord which was twisted round the paper enabled him to determine with greater facility the place where the image of each colour was formed with distinctness, for, in other places, the images of the threads were confused. For the blue half the distance of the image to the lens was less than in the case of the red half, which again proves that the blue is more refrangible than the red. These two experiments are the first described by Newton in his "Optics."

That which we call the natural colour of a body is the colour which is presented to us when it is illuminated by a very pure white light, as by sunlight. If its surface has the property of absorbing all the coloured rays of the spectrum with the exception of one, red for example, the body appears to us red, because it only reflects to our eye the red rays of the spectrum. If this surface absorbs but a limited number of coloured rays, the colour of the body will be that which proceeds from the mixture of the non-absorbed rays; and this explains the considerable number of colours and shades of bodies, which indeed are much more varied than those of which the spectrum itself is composed.

That substance which is able to reflect in an equal proportion all the colours which compose white light, is itself white, and it is brighter according as this proportion is greater. On the other hand, as this proportion diminishes, the white colour diminishes in intensity, and becomes a deeper and deeper grey, lastly attaining black, when the absorption of all the coloured rays of the spectrum is as complete as possible. Black bodies are therefore those whose molecular constitution is such, that all the rays which constitute white light are absorbed by their surface; whilst white bodies are those which reflect them all, and coloured bodies are those which reflect certain rays and absorb others. If this explanation is true, it is susceptible of many experimental verifications.

Let us take a white body and arrange it so that it only receives the yellow rays of the spectrum. This is easily done by placing it in a dark chamber, and admitting only the yellow rays of the spectrum obtained by means of a prism. The body will appear yellow. It would be red, green, blue, &c., if it were lighted up by red, green, or blue rays. On the contrary, a black body will remain black whatever the colour by which it is illuminated. Lastly, a red body will appear of a deep red, if it is lighted up with the light proceeding from the red rays of the spectrum, whilst it will appear black, if we expose it to the rays of other colours.

Experiment confirms these results. It is observed, however, that coloured bodies take the tint of the rays which illuminate them, even when these rays are not of the colour of these bodies; and that this tint is much brighter where there is greater analogy between their own colour and that of the rays with which they are illuminated. Thus "vermilion placed in red appears of a most brilliant red; in the orange and yellow, it seems an orange and yellow, but its brightness is less. The green rays also give it their colour, but, on account of the great inaptitude of the red to reflect the green light, it appears dark and dull; it becomes still more so in the blue, and, in indigo and violet, it is nearly black. On the other hand, a piece of dark blue or Prussian blue paper takes an extraordinary brilliancy, when exposed to the indigo rays. In green it becomes green, but not very bright; in red, it appears nearly black." (Sir John Herschel.)

Newton's theory must therefore be thus understood: that the surfaces of coloured bodies are generally apt to reflect the rays of a certain colour in a much greater quantity than those of other rays; and that gives them their predominant colour. These surfaces, nevertheless, do not entirely absorb the other rays, and that prevents them from being perfectly black when they are illuminated by coloured lights different from those which they generally reflect.

The colours of bodies are seldom identical with those composing the solar spectrum, as they are principally composite; evidence of which can be obtained by submitting them singly to analysis by the prism. This analysis gives a spectrum formed of various simple colours, the mixture producing the particular colour observed. It is sufficient to look at a coloured object, as a flower or a piece of dyed stuff, through a prism, to see that the edges of the image, parallel to the edge of the prism, are banded like the rainbow.

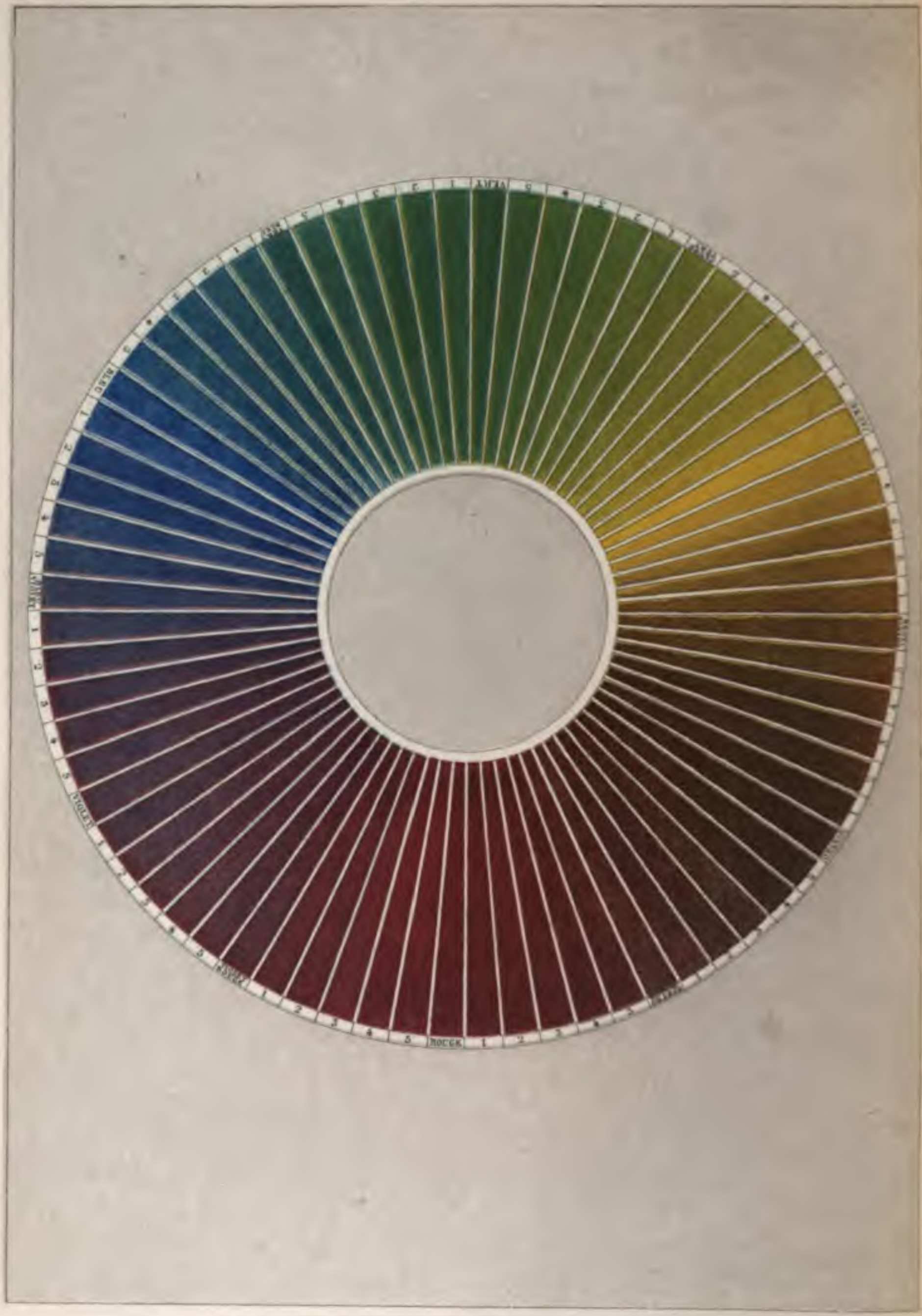
If, instead of illuminating a coloured body by the white light of the sun, or by one or other of the simple colours of which this light is composed, we use other luminous sources, such as the light of a lamp or artificial flames, the colour is found to be altered. Thus we all know that green appears blue by the light of a lamp. But let us first finish what we have to say of Newton's theory concerning the colours of non-luminous bodies.

In endeavouring to penetrate more deeply into the causes of this phenomenon, Newton supposed that the incident light is decomposed at the surface; one part is absorbed,—extinguished in opaque bodies and transmitted in transparent ones; the other part is reflected by the superficial molecules,—at a very little depth in opaque bodies, and at any depth in transparent ones. This explains why, in the latter, the colour of transmitted light is generally different from that of reflected light. For example, we have seen that gold reduced to extremely thin leaves allows a greenish blue light to pass through it, while its reflected colour is yellow, or reddish yellow. "Halley, having descended to a depth of several fathoms in a diving bell, saw that the upper part of his hand, on which fell the solar rays after passing through a glazed opening, was of a crimson colour; the under part, which was illuminated by light reflected from deep water, appeared green; whence Newton concluded that water allowed the red rays to pass through it and reflected the violet and blue." (Daguin.)

We must distinguish between light reflected regularly, or specularly, and that diffused light which is scattered from the surfaces of bodies. The first has nothing to do with the colour of bodies; and indeed we know that perfectly polished bodies represent the images of the bodies they reflect, coloured like the bodies themselves; while their own colour remains unperceived.

To what modification is light which is diffusely reflected submitted? How does the structure of bodies act on the different coloured rays, so as to reflect some and extinguish others? Is it the form, density, refractive power of the molecules, or, rather, is it these united elements which give place to the phenomenon of various colorations? These are excessively subtle questions, which cannot be answered with exactitude in the present condition of science.

PLATE I



CLASSIFICATION OF COLOURS

According to M. Chevreul

CHROMATIC CIRCLE OF PURE COLOURS

[illegible]

CHAPTER VIII.

COLOURS.

Classification of colours—Tones and scale of the colours of the solar spectrum, after the method of M. Chevreul—Chromatic circles of pure and subdued colours; tones and scales—Complementary colours.

THE white light of the sun, decomposed by means of a prism, produces a series of colours which correspond, as we have seen, to different degrees of refrangibility. These colours are, so to speak, infinite in number, as they pass from one end of the spectrum to the other by imperceptible shades; but it is customary to distinguish seven principal colours, the names of which, taken in their natural order, form a crude Alexandrian verse:

Violet, indigo, blue, green, yellow, orange and red.

Some physicists, believing in the possibility of reproducing some of these colours by the mixture of others,—green, for example, being obtained by the juxtaposition of yellow and blue, violet by that of blue and red, and so on,—have endeavoured to prove that the spectrum is only formed of three elementary colours. According to Brewster these colours would be red, yellow, and blue; according to Young red, green, and violet. The proportions in which they are mixed in the different parts of the spectrum would account for the variety of shades of which it is composed. In the present day, these theories are rejected; the experiments by which they were supported having been proved to be inexact. All the colours of the spectrum are therefore simple colours, the number of which can be considered as infinite; although, in practice, they are reduced to seven principal colours.

White is not a simple colour, but, on the contrary, the most complex of the composite colours. Black is not a colour; it is the complete absence of all light. As to the composite colours which natural bodies present to us, they are due to combinations, in various proportions, of all the elementary colours.

A very simple experiment proves that the combination of all the rays of the spectrum is necessary to produce perfect light. It consists in intercepting a certain portion of the spectrum, before it falls on the lens which is used for the recomposition of the light. Thus, if the violet be intercepted, the white will acquire a tinge of yellow; if the blue and green be successively stopped, this yellow tinge will grow more and more ruddy, and pass through scarlet to orange and blood-red. If, on the other hand, the red end of the spectrum be stopped and more and more of the less refrangible portion thus successively abstracted from the beam, the white will pass first into pale, and then to vivid, green, blue-green, blue, and finally into violet. If the middle portion of the spectrum be intercepted, the remaining rays, concentrated, produce various shades of purple, crimson, or plum-colour, according to the portion by which it is thus rendered deficient from white light; and, by varying the intercepted rays, any variety of colours may be produced; *nor is there any shade of colour in nature which may not thus be exactly imitated with a brilliancy and richness surpassing that of any artificial colouring.*

The number of composite colours, obtained by the combination of simple colours, or the different coloured rays of the spectrum, increases to an almost indefinite amount. But we shall presently see that it is possible to increase them still more, either by the addition of a certain quantity of white light, or by the mixture of black in various proportions.

Two colours which, by their combination, produce white are called *complementary colours.*

There is a very simple method of determining the groups of colours which possess this property: it consists in the interception, as it issues from a lens, of a portion of the convergent beam about to meet at the focus. This portion received on a second prism will be deviated, and will give a colour which will be evidently complementary to the colour produced at the focus of the lens, as before their separation they formed white.

Helmholtz discovered, by a different process, which consisted in receiving the spectrum colours through slits in a screen and then concentrating them by a lens, that there is an indefinite number of groups of two colours susceptible of forming, by their mixture, perfect white. The following are some of the results obtained by that physicist:—

Complementary Colours.	Intensities of the two Colours.		
Violet — greenish yellow	1	—	10
Indigo — yellow	1	—	4
Blue — orange	1	—	1
Greenish blue — red	1	—	0·44

The numbers which follow these groups measure the relative intensities of each of the colours and refer to a bright light; they vary when the incident light itself varies in intensity. Helmholtz has devised an extremely simple method of studying the resultant of the mixture of two colours, one of the first, the other of the second colour. When an unsilvered glass is placed vertically between them, one of the discs is seen directly; the other through the transparent plate. Moreover, the first is seen a second time, by reflection. If it is then placed in such a position that its image appears superposed upon the disc seen through the glass, the two colours will be found naturally blended, and one can easily judge of the shade produced by their composition. Thus, also, two discs, coloured, the one by chrome yellow, the other by cobalt blue, produce pure white; which proves that these colours are complementary.

To sum up, a simple or composite colour always has its complementary colour; moreover, it has an infinity of them, for if to the complementary colour we add white light in variable proportions, the resultant can only be white. But this rule can only be applied to clear colours, that is to say, those which are not altered by any proportion of black; in this case, instead of perfect white, a grey or greyish-white would be obtained.

Lastly, the mixture of complementary colours only produces white when it is not a material mixture; if material colours are used, moistened in whatever way, or even in a pulverulent state, the mixture will only give a more or less decided grey. If the colours, whether simple or composite, are indefinite in number; if the mixture in different proportions of white or black again multiplies that number; it is no less true that the eye can only appreciate a limited quantity. Yet, if it were possible to collect in one scale all the shades of colours presented to us by Nature, and to distinguish them from each other, we should be astonished at the richness and magnificence of that palette. The leaves and flowers of plants, the skins of animals, the brilliant colours which the feathers of birds possess, the wings of butterflies and other insects, shades of different minerals and shells, would furnish elements of the innumerable series of natural colours, and would pass from one shade to another by imperceptible gradations. Thus we could have a classification of colours derived from natural objects.

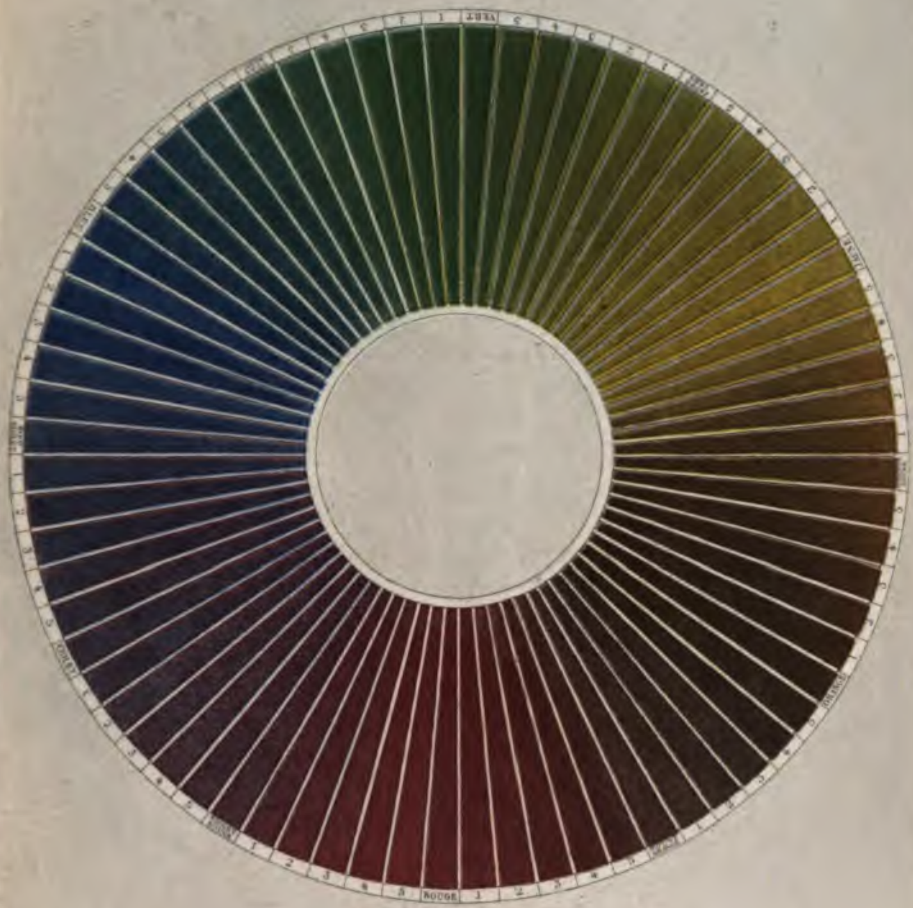
Colours used in the arts are probably much more restricted; we can nevertheless form an idea of their number by this fact—that the Romans used, it is said, more than 30,000 tints in their mosaics.

But even this number, precisely because it is considerable, causes the want to be felt of a proper classification of colours and their shades, which would enable them to be defined by showing their relationship to a fixed type, determined once for all. We all know that, in industries and the arts, the nomenclature of colours is very arbitrary or, at least, varies in one art or industry from another: the names are borrowed from natural objects, minerals, flowers, fruits, and animals, but there is no line of gradation between them. In order to obviate the inconveniences resulting from this confusion, M. Chevreul, celebrated for his chemical labours and his study of colours, proposed a classification of colours and their shades. The principles and basis of this we will now describe.

According to M. Chevreul, a substance possessing any one of the colours of the spectrum can only be modified in four different ways:

1. By *white*, which reduces it in intensity.
2. By *black*, which diminishes its specific intensity.
3. By a *certain colour*, which changes the specific property without rendering it less bright.
4. By a certain colour which changes the specific property and renders it less bright, so that if the effect is carried to the highest degree, it results in black or normal grey, represented by black mixed with white in a certain proportion.

To express all these modifications, M. Chevreul uses the following expressions, which once defined can no longer be equivocal:—



CLASSIFICATION OF COLOURS

According to M. Chevreul

CHROMATIC CIRCLE TONED DOWN BY $\frac{3}{10}$ BLACK

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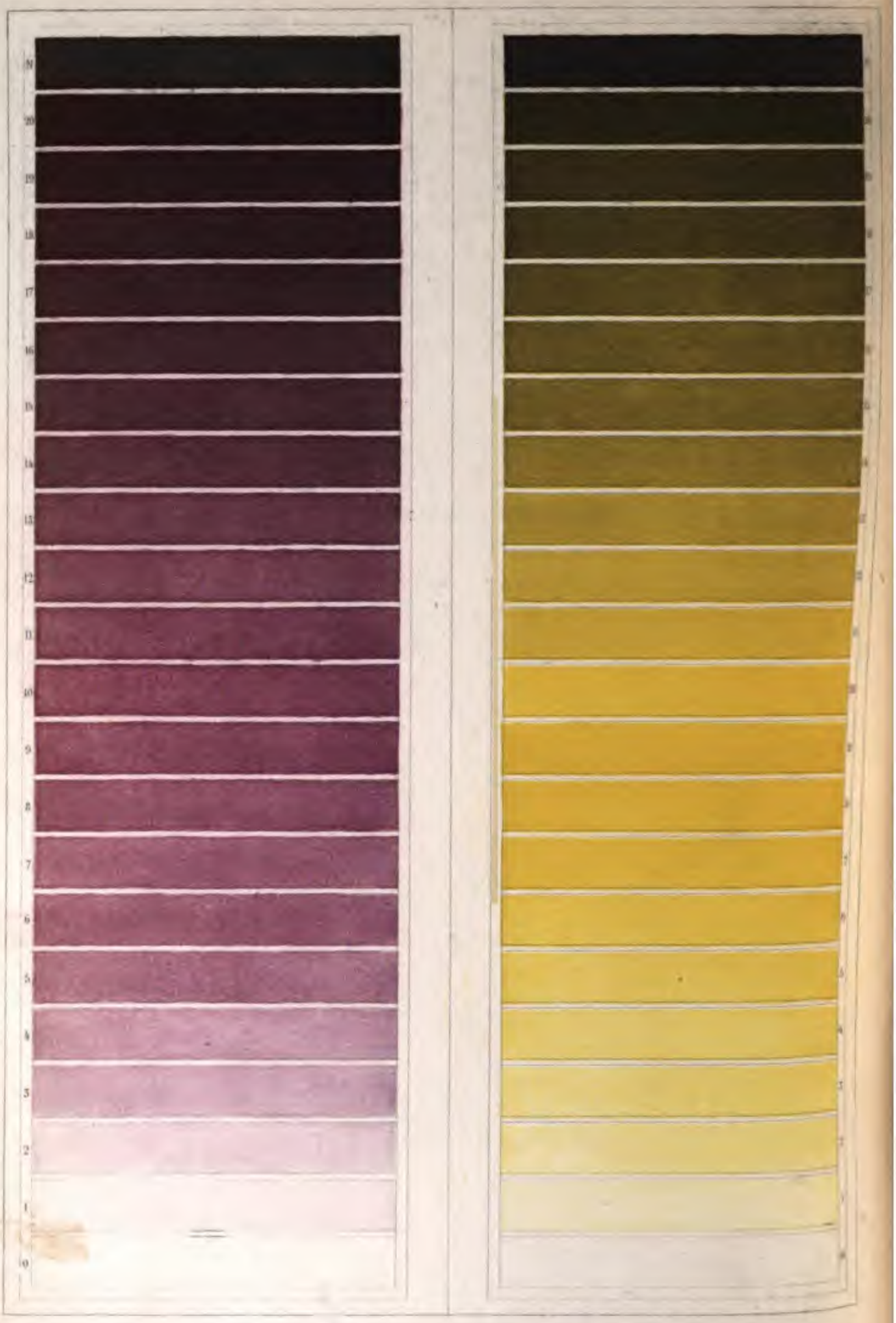

CHROMATIC SCALES

violet & yellow

He calls the *tones* of a colour the different degrees of intensity to which this colour is susceptible, according as the matter which presents it is pure or simply mixed with white or black; the *scale*, the whole of the tones of the same colour; the *shades* of a colour, the modifications which it undergoes by the addition of another colour which changes it without rendering it less bright; lastly, the *subdued scale*, the scale whose light tones as well as the dark ones are tarnished with black. M. Chevreul obtained a scale sufficiently extensive for the principal colours and their tones and shades by the following means:—

Having divided a circle into seventy-two equal sections, he placed, at equal distances, three patterns of tinted wool, one red, another yellow, the third blue; as fresh and pure as possible, and of the same intensity of colour. Between these three sections, and at an equal distance from each, he placed orange between the red and yellow, green between this latter and the blue, and violet between the blue and red. By continuing in the same manner successive intercalations of intermediate colours and shades, he at last obtained what he called a chromatic circle of fresh colours, so as to reproduce the spectrum of solar light. Plate I. is a reproduction of this first circle.

When these seventy-two shades were obtained, he took each of them to make a complete scale formed by the addition of increasing quantities of white and black, in order to have ten subdued tones and ten tones of the same colour rendered clearer by white. Each scale therefore comprised, from pure white to pure black, which were the extremities, twenty different tones, of which the pure colour is the tenth, starting from white. Plate III. shows the two scales of yellow and violet reproduced according to the types given by M. Chevreul.[1]

From this first combination there are already 1,440 different tones, all deduced from the chromatic scale of pure colours; but in successively subduing the seventy-two tones of this circle by the addition of 1, 2, 3, &c. tenths of black, nine circles of subdued colours are formed (see in Plate II. the chromatic circle of subdued colours, $\frac{1}{10}$ of black); and each of the seventy-two tones which they comprise becoming in its turn the type of a scale of twenty new ones proceeding from white to black, there follows, for the complete series, a scale of 14,400 tones, to which must be again added the twenty tones of normal grey, which makes 14,420 different tones.

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[1] "Des Couleurs et de leurs Applications aux Arts industriels à l'aide des Cercles chromatiques." The text of this work is accompanied by twenty-seven steel engravings, coloured by René Digeon. Thanks to the kind permission of M. Chevreul, we have been able to reproduce three of these beautiful plates here.

It is evident that such an extensive scale ought to suffice for most of the scientific and industrial applications, and will most frequently exceed the wants of artists. Unfortunately, the rigorously exact material reproduction of all these colours is of great difficulty, and it is no less difficult to preserve the types when once they are obtained. The chromatic construction of M. Chevreul must be reproduced in unalterable colours,—for instance, in pictures enamelled on porcelain. Scientific research would not be less interested than the arts to possess fixed types, to which the colours of natural objects, so often changed by time, would be brought back again by the help of the order of numbers, and thus made easy of reproduction.

CHAPTER IX.

LINES OF THE SOLAR SPECTRUM.

The discoveries of Wollaston and Fraunhofer; dark lines distributed through the different parts of the solar spectrum—Spectral lines of other luminous sources-Spectral analysis; spectrum of metals; inversion of the spectra of flames—Chemical analysis of the atmosphere of the sun, of the light of stars, nebulæ, and comets.

NEWTON, in studying the different parts of the solar spectrum, by means first of circular and afterwards of elongated apertures, could not distinguish any indication of the precise limits of its various colours: they appeared to blend with one another in an imperceptible manner and without interruption. He was persuaded, however, by his experiments, that the coloured rays which constitute white light possess, from the extreme red to the extreme violet, all possible degrees of refrangibility, and he regarded each of these rays as simple and homogeneous, imagining that the light decomposed by the prism was spread out in a continuous manner throughout the whole spectrum.

It is curious that Newton did not go further—that he did not reduce the aperture to a fine line of light, in which case the colours would have been seen in all their purity, and would not have been mixed and confused by the overlapping of each colour on its neighbour.

This step in advance was reserved for the beginning of the present century, and then a great discovery was made. It was found that here and there in the different colours there were gaps in the light; in other words, that there were dark lines in the sun's spectrum. This was first detected by Wollaston in 1802, but the discovery was independently made and largely elaborated by Fraunhofer.

Joseph Fraunhofer, who was born in 1787, at Straubing, a little town in Bavaria, was the son of a glazier. He was at first a worker in glass, but, by labour and perseverance, succeeded in meriting the reputation of being the most ingenious and learned optician of our century. Fraunhofer did not confine himself to bringing the construction of optical instruments to a perfection then unknown; but, a consummate observer, he employed the instruments which he manufactured, to make various discoveries, amongst which, that to which we have referred is one of the most curious and most fruitful in its results.

In the attempt to measure the refractive indices of the coloured rays, and to find particular points in the spectrum capable of being used as marks, Fraunhofer discovered the great fact, that the light of the solar spectrum is not continuous, that it is divided by a multitude of fine black lines, which form so many sharp interruptions in the luminous band.

In this experiment, which required the most delicate manipulation, he made use of a prism of pure flint-glass, free from striæ, upon which a beam of sunlight was caused to fall, which had previously passed through a very fine slit parallel to the edge of the prism. The spectrum thus obtained, when observed by means of a magnifying glass, showed him, instead of a continuous band in which the colours blended with each other without interruption, a ribbon crossed in the direction of its width, with numerous dark and black lines very unequally spread over the spectrum. The distribution of these lines did not appear to have any relation with the tints of the principal colours.

Fraunhofer varied this experiment in a variety of ways; but, as long as the luminous source was sunlight, either direct or reflected, the same dark lines always appeared, and preserved the same relations of order and intensity. If, instead of a flint glass prism, a prism of any other substance, liquid or solid, is employed, the distances only of the lines vary, but otherwise they always occupy the same positions relative to the colours of the spectrum.

The illustrious optician of Munich studied this remarkable phenomenon with infinite care: he determined, with great precision, the positions of 580 dark lines, and, for use as marks and comparison, he distinguished among this number eight principal lines, which he called by the first letters of the alphabet. The solar spectrum of Plate IV. shows the position of these lines, as they were obtained with a prism filled with bisulphide of carbon. The lines A, B, C, are all found in the red, the first at the extremity of the spectrum, the second at the middle of the red, and the third at a little distance from the orange. The double line D forms nearly the limit of the orange near the green; E in the middle of this last colour; F at the middle of the blue; G and the double line H are, one at the end of the indigo towards the blue, the other at the end of the violet. Since 1817, when Fraunhofer observed the lines which bear his name, new dark lines have been noticed, and, at the present day, more than 2,000 have been mapped by Kirchhoff and Ångström.

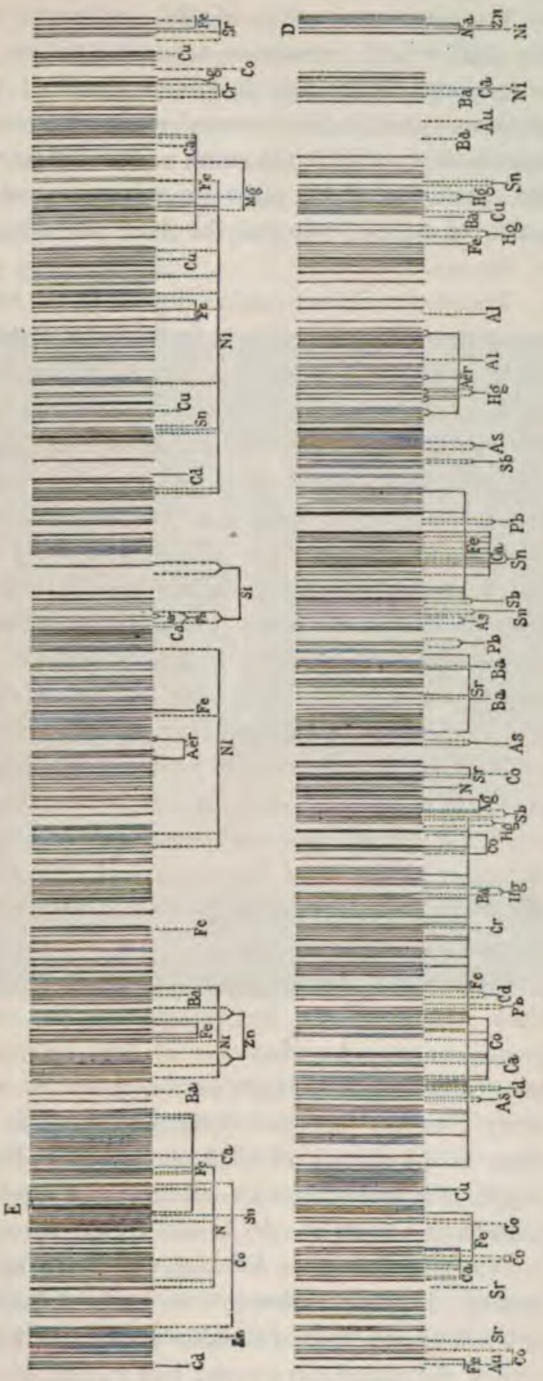


FIG. 240.—A fragment of the solar spectrum.

[illegible]

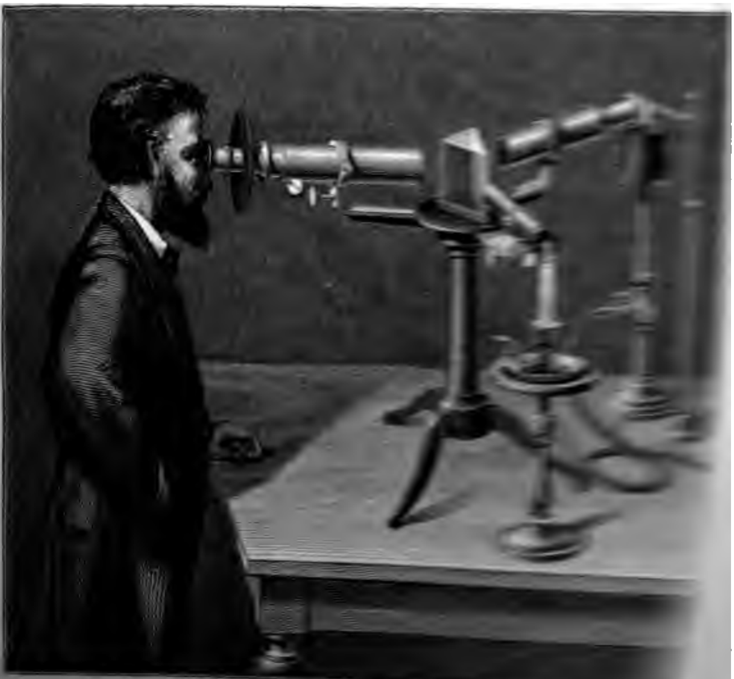
[illegible] the lines which [illegible] he also applied [illegible] spectra of other sources of [illegible] he found the same lines in [illegible] such as clouds or pure [illegible] the lines were the same, but they possessed [illegible] the spectrum of the brightest star, [illegible] crossed by dark lines; but much [illegible] in the same manner as in the [illegible] he discovered that the lines varied in [illegible] Lastly he applied the same method of observa- [illegible] and instead of dark lines, he saw in [illegible] certain number of bright lines.

[illegible] experiments which have served as starting [illegible] the whole of which now [illegible] important branches of optics, and aid [illegible] and delicate method of analysis. [illegible] to give some idea of this method, known

[illegible] as we have seen, striped with dark [illegible] interruptions in the emission of light, and [illegible] what was at first believed, that in the light [illegible] these light sources there are not rays which possess [illegible] possible degree of refrangibility. The contrary effect takes place in the spectra of all incandescent bodies, either in the solid, [illegible] densely gaseous condition: the spectra of these lights are continuous: there are no br[illegible]s in the spectrum.

Vapours and gases, h[illegible] which are not den[illegible] results. If we introd[illegible] or a spirit-lamp, [illegible] ture of the so[illegible] longer observed, but bright lines separated [illegible] dark, intervals: Fraunhofer had already [illegible] rendered incandescent by the electric spark [illegible]

Since his time, the fact has been [illegible] by various methods. It has been [illegible] of metallic vapours, and gases when [illegible] and position, according to the metal [illegible] as the pressure of the gas is altered.



[illegible]

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[illegible] this has been done.

[illegible] the slit of a spectroscope, and an eyepiece. This arrangement, which is a great improvement upon that adopted by Fraunhofer, is due to an English optician of great celebrity, Mr. Simms.

To obtain the spectrum of the vapour of a metal, for instance that of sodium, we introduce into the flame of a lamp a platinum wire impregnated with a concentrated solution of salt, of which this metal forms the base, sea-salt (chloride of sodium), for instance. We soon perceive a yellow ray of great intensity and sharp outline. This is the only line of the sodium spectrum. (Plate I.)

The vapour of lithium gives two principal lines, one a pale yellow, the other red and bright; potassium gives two characteristic lines, red and violet, accompanied by yellow and green lines; calcium gives a very bright green line, one orange and one blue; strontium gives eight lines, six of which are red, one orange and one blue; barium, two green lines; thallium, one green line, remarkable for its brilliancy.

The vapours of a great number of simple bodies have thus been studied, the bright lines of their spectra discovered, and their position fixed. No two vapours or gases have the same spectrum. Hence results a new method of analysis, which is so delicate that a millionth part of a milligramme of sodium is sufficient to immediately show the characteristic yellow ray of the spectrum of this metal. Two German chemists and physicists, MM. Kirchhoff and Bunsen, were the first to bring spectrum analysis to a high degree of precision. "I take," says M. Bunsen, "a mixture of the chlorides of alkaline metals and earths—sodium, potassium, lithium, barium, strontium and calcium—containing at most a hundred thousandth of a milligramme of each of these substances. I place this mixture in the flame and observe the result. At first, the intense yellow line of the sodium appears on a background of a continuous very pale spectrum; when it begins to be less sensible and the sea-salt is volatilized, the pale lines of the potassium appear; they are followed by the red line of the lithium, which soon disappears, whilst the green rays of the barium appear in all their intensity. The salts of sodium, potassium, lithium, and barium are therefore entirely volatilized; a few instants after, the calcium and strontium lines come out, as if a veil has been removed, and gradually attain their form and characteristic brilliancy."

By the help of spectrum analysis, the presence of sodium has been determined in the air and the dust floating about in a room. The sensibility of the reaction of this metal is so great, that spectroscopic observers are obliged to take all kinds of precautions to prevent the appearance of the sodium line; even if we dust a book near the instrument, the yellow sodium line immediately appears.

Four new metals have been discovered by this method: the two first, cæsium and rubidium, by MM. Bunsen and Kirchhoff; the third, thallium, by Mr. Crookes and M. Lamy; the fourth, indium, by MM. Reich and Richter. The name cæsium is given from the two blue lines in its spectrum; rubidium from the red lines which characterize the spectrum of this metal; the name thallium recalls a beautiful green line, and that of indium a blue line near the indigo.

In these various lines then we have the power of detecting the gases and the vapours of the various elements; but this is not all. Recent researches undertaken by Frankland and Lockyer have shown that certain spectra undergo great changes by varying the pressure, and that some lines in various spectra widen out, and become diffused from increase of pressure, which also, when long continued, changes a typical gaseous spectrum—hydrogen, for instance—into a perfectly continuous one, similar to those of solids or liquids.

Frankland and Lockyer have also shown that the various spectra produced by varying the pressure can be, to a certain extent, reproduced by varying the quantity of any given vapour in a mixture. Such researches as these give us ground for hoping that in time this method of analysis may be employed quantitatively as well as qualitatively, and explain Bunsen's experiment to which we have before referred.

But we do not confine the power of the spectroscope to terrestrial matter; it has gone further: problems can be investigated and solved by its means which had appeared inaccessible to human investigations; the study of the chemical composition of the heavenly bodies, that of the sun and stars—these suns so prodigiously distant from us; of nebulæ, which telescopes show us plunged in the abysses of the ether at such distances that the imagination can scarcely fathom the depth, and of comets.

Let us show in a few words how this has been done.

If we place a jet of gas before the slit of a spectroscope, and lessen it so that it is scarcely perceptible, and burns with a bluish flame, we observe that, in this condition, it will give no spectrum; there is complete darkness behind the prism. But, if a metallic salt is introduced into the flame, sea-salt for instance, the yellow ray of the sodium immediately appears, as we have just seen. If, at the same time, and in the same instrument, we introduce a solar ray in such a manner that the sodium spectrum and the solar spectrum are superposed, a perfect coincidence will be noticed in the position of the sodium yellow ray, and Fraunhofer's double dark line D.

Now, for the sunlight let us substitute the intense light known as Drummond's light—obtained by heating a piece of lime in a gas burner into which a current of oxygen gas is introduced. The spectrum of this light, seen alone, shows a bright spectrum of perfect continuity; that is, containing none of the dark lines of the solar spectrum. But if we interpose between the Drummond's light and the slit of the spectroscope a sodium flame, the yellow sodium line now gives place to a black line occupying precisely the same position as the bright line did when the brighter light source was not behind it.

It is this phenomenon which M. Kirchhoff calls the "inversion of the spectra of flames."

It has been proved in regard to a great number of metallic spectra. "If we cause," he says, "a solar ray to pass through a flame of lithium, we see in the spectrum, in place of the usual red line, a dark line, which rivals by its sharpness the most characteristic of Fraunhofer's lines, and which disappears on removing the lithium. The reversal of the bright lines of other metals is not so easily effected; nevertheless, M. Bunsen and myself have been fortunate enough to invert the brightest lines of potassium, strontium, calcium, and barium. . . ."

Now, what inference is to be drawn from this singular fact? It is that metallic vapours, endowed with the property of abundantly emitting certain coloured rays, in preference to others, absorb these same rays when they emanate from a more intensely luminous source and traverse them. Thus, sodium light, which emits yellow rays, absorbs the yellow rays of Drummond's light on their passage through it. Hence results the black line, which occupies the same position in the continuous spectrum which the bright sodium line previously held.

If this absorption is a general fact, *it must be concluded that the black lines observed in the solar spectrum, indicate the reversal of as many bright lines by metallic vapours in the atmosphere of the sun.* This atmosphere, to us, acts the part of the sodium flame, and the bright light of the sun's body that of the Drummond's light in the same experiment.

This magnificent discovery, which has at one bound enabled us to become familiar with the constituents of the atmospheres of all the stars of heaven which are bright enough to show a spectrum, is generally accorded to Kirchhoff and Bunsen, but the credit of it is really due to an Englishman, Professor Stokes, who taught it as early as 1852, while Kirchhoff and Bunsen did not announce their discovery till 1859.

The observational and experimental foundations on which Professor Stokes rested his teaching were as follows:[1]—

(1) The discovery by Fraunhofer of a coincidence between his double dark line D of the solar spectrum and a double bright line which he observed in the spectra of ordinary artificial flames.

(2) A very rigorous experimental test of this coincidence by Professor W. H. Miller, which showed it to be accurate to an astonishing degree of minuteness.

(3) The fact that the yellow light given out when salt is thrown on burning spirit consists almost solely of the two nearly identical qualities which constitute that double bright line.

(4) Observations made by Stokes himself, which showed the bright line D to be absent in a candle-flame when the wick was snuffed clean so as not to project into the luminous envelope, and from an alcohol flame when the spirit was burned in a watch-glass. And

(5) Foucault's admirable discovery (*L'Institut*, Feb. 7, 1849) that the voltaic arc between charcoal points is "a medium which emits the rays D on its own account, and at the same time absorbs them when they come from another quarter."

The conclusions, theoretical and practical, which Professor Stokes taught, and which Professor Thomson gave regularly afterwards in his public lectures in the University of Glasgow, were :—

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[1] See Sir W. Thomson's Address as President of the British Association in 1871.

(1) That the double line D, whether bright or dark, is due to vapour of sodium.

(2) That the ultimate atom of sodium is susceptible of regular elastic vibrations, like those of a tuning-fork, or of stringed musical instruments; that, like an instrument with two strings tuned to approximate unison, or an approximately circular elastic disk, it has two fundamental notes or vibrations of approximately equal pitch; and that the periods of these vibrations are precisely the periods of the two slightly different yellow lights constituting the double bright line D.

(3) That when vapour of sodium is at a high enough temperature to become itself a source of light, each atom executes these two fundamental vibrations simultaneously; and that therefore the light proceeding from it is of the two qualities constituting the double bright line D.

(4) That when vapour of sodium is present in space across which light from another source is propagated, its atoms, according to a well-known general principle of dynamics, are set to vibrate in either or both of those fundamental modes, if some of the incident light is of one or other of their periods, or some of one and some of the other; so that the energy of the waves of those particular qualities of light is converted into thermal vibrations of the medium and dispersed in all directions, while light of all other qualities, even though very nearly agreeing with them, is transmitted with comparatively no loss.

(5) That Fraunhofer's double dark line D of solar and stellar spectra is due to the presence of vapour of sodium in atmospheres surrounding the sun and those stars in whose spectra it had been observed.

(6) That other vapours than sodium are to be found in the atmospheres of sun and stars by searching for substances producing in the spectra of artificial flames bright lines coinciding with other dark lines of the solar and stellar spectra than the Fraunhofer line D.

Studying from this point of view the dark lines of the solar spectrum, Bunsen and Kirchhoff were enabled to prove the coincidence of a great number of them with the bright lines of certain metals. For example, the seventy bright lines of iron, different in colour, width, and intensity, coincide, in every point of view, and precisely in the same way, with the seventy dark lines of the sun; which makes it impossible to doubt that, in the solar atmosphere, iron exists in the state of vapour. In Fig. 240, a certain number of these lines are seen, marked Fe. The same *savants* discovered the presence of nine other simple bodies in the atmosphere of the sun,—hydrogen, copper, zinc, chromium, nickel, magnesium, barium, calcium, and sodium; and it is probable that to this list we may add cobalt, strontium, and cadmium. This work has recently been extended by the researches of Ångström and Thalen. From the absence of the characteristic lines of other metals, such as gold, silver, platinum, &c. in the solar spectrum, it was believed, at first, that these bodies are not found in the sun, at least in the outer strata which form its atmosphere; but this conclusion is too absolute, as is shown by new researches due to M. Mitscherlich, which may probably be explained by the observations of Frankland and Lockyer before alluded to.

We sum up then what we have stated, as follows:—

Solids, liquids, and vapours and gases when dense, give us continuous spectra without bright lines. Vapours and gases when not dense give us continuous spectra with bright lines.

Changes in the lines composing the spectrum, and in the thickness of the lines, are brought about by changes of pressure.

Gases and vapours absorb those rays which they themselves emit if a brighter light source is behind them; this absorption is continuous or selective, as the radiation is continuous or selective.

This is one among many results brought about by employing many prisms to give considerable dispersion, and therefore a very long spectrum. There is another which reads almost like a fairy tale; so impossible does it at first sight appear, that we can thus measure the velocities of the stars in their paths, or the rate at which solar storms travel by such means: but of this, more presently.

One of the recent advances in the application of the spectroscope to the examination of the celestial bodies, arises from the following considerations:—

The light from solid or liquid bodies is scattered broadcast, so to speak, by the prism into a long band of light, called a continuous spectrum, because from one end of it to the other the light is persistent.

The light from gaseous and vaporous bodies, on the contrary, is most brilliant in a few channels; it is *husbanded*, and, instead of being scattered broadcast over a long band, is limited to a few lines in the band—in some cases to a very few lines.

Hence, if we have two bodies, one solid or liquid and the other gaseous or vaporous, which give out exactly equal amounts of light, then the bright lines of the latter will be brighter than those parts of the spectrum of the other to which they correspond in colour or refrangibility.

Again, if the gaseous or vaporous substance gives out but few lines, then, although the light which emanates from it may be much less brilliant than that radiated by a solid or liquid, the light may be so localized, and therefore intensified, in one case, and so spread out, and therefore diluted, in the other, that the bright lines from the feeble light source may in the spectroscope appear much brighter than the corresponding parts of the spectrum of the more lustrous solid body. Now here comes a very important point: supposing the continuous spectrum of a solid or liquid to be mixed with the discontinuous spectrum of a gas, we can, by increasing the number of prisms in a spectroscope, dilute the continuous spectrum of the solid or liquid body very much indeed, and the dispersion will not seemingly reduce the brilliancy of the lines given out by the gas; as a consequence, the more dispersion we employ the brighter relatively will the lines of the gaseous spectrum appear.

Let us apply this to the prominences seen round the sun in an eclipse.

The reason why we do not see the prominences every day is that they are put out by the tremendous brightness of our atmosphere near the sun, a brightness due to the fact that the particles in the atmosphere reflect to us the nearly continuous solar spectrum. There is, as it were, a battle between the light proceeding from the prominences and the light reflected by the atmosphere, and, except in eclipses, the victory always remains with the atmosphere.

We see, however, in a moment, that by bringing a spectroscope on the field we might turn the tide of battle altogether, since the prominences are gaseous, as the reflected continuous spectrum is dispersed almost into invisibility, the brilliancy of the prominence lines scarcely suffering any diminution by the process. This reasoning was first successfully put to the test by a distinguished French physicist, M. Janssen, in 1868.

Is it not wonderful, that the dispersion of light not only explains with such accuracy the chemical composition of the bodies whence it emanates, and preserves, after a passage of millions upon millions of miles, the traces of absorption of various rays,—a certain indication of the presence of simple bodies suspended in an atmosphere which astronomers only suspected, and the existence of which is thus confirmed,—but enables us to measure velocities, and even to study the meteorology of our sun? as we shall see shortly. Spectrum analysis thus applied to sun, stars, planets, nebulæ, comets, furnishes valuable indications as to the intimate constitution of these bodies, and solves problems which the most powerful optical instruments would doubtless never have unravelled.[1] It is thus that the sciences mutually help each other: progress realized by one of them is nearly sure to promote new discoveries in others.

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[1] For fuller particulars on this branch of the inquiry see "The Heavens," a companion work to this, published by Mr. Bentley.

CHAPTER X.

SOLAR RADIATIONS.—CALORIFIC, LUMINOUS, AND CHEMICAL.

Divisions of the spectrum ; maximum luminous intensity of the spectrum—Obscure or dark rays ; heat rays ; chemical rays—Fluorescence, calorescence.

THE different parts of the solar spectrum are distinguished not only by the unequal refrangibility of the rays which produce them, by their colours, and by the greater or less vividness of their brilliancy, but by their warming or calorific action, as well as by their power of modifying, to different degrees, certain substances in a chemical point of view.

When the luminous intensities of the seven principal colours are compared together in the same spectrum, we at once perceive that the brightest portion is found in the yellow. From this point the brightness diminishes towards the red and the violet. We see, moreover, that the colours can be naturally divided into two classes: the first comprising the more luminous colours, red, yellow, and green; the second, the darker colours, blue, indigo, and violet; there are continuations of the spectra in both directions which are invisible to the eye. Thus we have the *ultra-red* and the *ultra-violet* rays. In fact we must look upon the spectrum as composed of heat-rays, light-rays, and chemical rays, the second only of which are completely visible to us. A very simple experiment enables us to judge of the difference which exists between the illuminating powers of different colours: if we take the pages of a book, and receive the spectrum on the printed portion of the paper, we shall find that the characters can be easily read in the orange, yellow, and green; whilst it is scarcely possible to read those which receive the other colours.

According to Fraunhofer, who studied photometrically the luminous intensities of the colours of the spectrum, the maximum brightness is found between the lines D and E; but this point is nearer D, and its distance from this last line is about the tenth part of the total interval D E. More precise methods have determined numerically the illuminating power of the spectrum at the points where it is cut by the eight principal lines of Fraunhofer. Taking the maximum brightness at a thousand, the following are the luminous intensities:—

Colours.	Luminous intensities.	Lines.
Extreme red	imperceptible	A
Red	32	B
Red	94	C
Orange	640	D
Yellow	1000	
Green	480	E
Blue	170	F
Indigo	31	G
Extreme violet	6	H

This refers only to the relative intensities of the colours of the solar spectrum, not to those of other spectra, nor to the similar colours of various substances. These are pure colours, without mixture of white or black: mixtures of black with primitive colours include as we have seen in explaining the classification of colours by M. Chevreul, all the category of dark colours called browns; the tints of which are no longer those of the corresponding ones in the spectrum: the same holds with clear and bright colours obtained by increasing proportions of white.

Some time ago the question arose whether the heat of the solar rays was equally distributed throughout the whole length of the spectrum, or if, on the contrary, the differently coloured rays, besides their difference of luminous intensity, also possessed unequal calorific powers. Some experiments made by the Abbé Rochon led to the belief that the most luminous rays were also the most calorific, so that the maximum heating was in the yellow; but other physicists assumed that this maximum was in the red, or rather beyond the extreme red. According to Seebeck (1828), all these opinions are true, because heat, transmitted by the coloured rays, being unequally absorbed according to the nature of the prism, the position of the maximum calorific rays must depend on the substance of this latter; and indeed, this physicist showed that the most intense calorific rays are those of the yellow, orange, red, and extreme red, as the solar light is dispersed by the aid of prisms formed with water, sulphuric acid, ordinary glass, or English flint-glass. As rock-salt absorbs little or no heat, either dark or luminous, the calorific powers of the differently coloured rays can be best compared by using a prism of this substance. Working thus, Melloni proved that the temperature of these rays increases in passing from the violet to the red; and that the maximum calorific effect is produced beyond the red, at a distance from the extreme limit of the red equal to that which exists between this and the yellow. Beyond this point the heat decreases; but is still perceptible when it has reached a distance from the red equal to the whole extent of the luminous—that is, the visible—spectrum.

This remarkable result acquired a fresh degree of importance when the solar rays were studied from another point of view. We all know the influence of sunlight on material colours, when these colours are given either to stuffs, paper, wood, or other organic substances. Coloured curtains fade with daylight; yellow cotton or linen is bleached when exposed to the sun. We understand, in the present day, how necessary light is to the complete development of health, and even to the life of vegetables and animals.

Now, these multiple influences, to which we shall have occasion to return, consist in a series of chemical actions in the decompositions or combinations of substances. Chlorine and hydrogen, which in the dark have no action on each other, combine when exposed to the light, forming hydrochloric acid. If the flask which contains them is exposed to the diffused daylight, the combination is effected slowly; in the solar rays, it takes place suddenly, and explosion is the result. Light decomposes salts of gold, silver, and platinum. Heliography, which was discovered by Niepce and Daguerre, and all actual processes of photography, are based on the chemical action of luminous rays, either from the sun, moon, or other sufficiently intense luminous source. We shall describe these further on; we will now indicate the phenomena themselves. Mr. Rutherford, who has photographed the spectrum with unequalled success, has determined that the maximum chemical effect lies near the line G.

The same question presents itself here as in regard to the illuminating and heating effects. We require first to know if the different regions of the solar spectrum are endowed with the same faculty of chemical action, or if this efficacy varies in different parts of the spectrum. Now Scheele, who in 1770 had ascertained the action of light on chloride of silver, discovered also that the coloured rays of the spectrum act unequally in producing this decomposition. It was afterwards discovered not only that the chemical rays increase in intensity in passing from red to violet to such a degree that the chloride in question blackened in a few minutes, when it received the concentrated rays of the violet part of the spectrum, whilst it required several hours, if it received rays between and including the green and red rays; but that beyond the extreme violet, in the dark portion of the spectrum, chemical action continued at a considerable distance beyond the luminous portions.

The intensity of chemical radiation, which varies for one substance according to the position of the rays in the spectrum, does not attain its maximum at the same point for different substances. This maximum is not the same for salts of silver as for salts of gold, nor for the latter as for salts of potassium.

The following phenomenon is worthy of remark: the spectrum which may be called chemical, to distinguish it from the luminous and heat spectrum, possesses rays like the first of those. In the dark portions of a spectrum photographed by means of chloride of silver, white lines may be observed which indicate an interruption of chemical action, and their position coincides precisely with Fraunhofer's line. But, beyond the violet, other rays exist, which naturally have no corresponding ones in the luminous spectrum.[1]

Professor Stokes, by enabling us to see these invisible rays, has given us the reason why they are ordinarily invisible. If we receive these rays on a screen washed with a solution of sulphate of quinine, they are at once visible as blue light; we have the phenomenon of *fluorescence*, which can also be rendered visible by other means.

The explanation of the phenomenon of *fluorescence* is that the ultra-violet rays, which move too rapidly for our eyes, have their velocity retarded—toned down—and are thus brought within the range of visibility and known colour. The heat rays have been similarly rendered visible by Professor Tyndal in the phenomenon of *calorescence*.

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[1] Nevertheless, the most refrangible rays, like the violet, are not completely invisible. According to J. Herschel, the ultra-violet rays, acting on the retina, give a shade called by him lavender-grey.

Thus, the solar spectrum is more complete than was at first believed, by studying only the impressions produced on the eye. It appears to be formed of three superposed spectra; one giving light and colours; another, the action of which is sensible to the thermometer, reveals to us the warming or calorific property of the solar rays; and lastly, a third teaches us how much their chemical activity varies. But, do three kinds of rays exist, as was at first supposed? Delicate experiments, among which we only quote that which implies the identity of the rays of the luminous spectrum and those of the chemical spectrum, prove that there is identity between the different radiations. The same rays produce, in one place, varied colours; in another, variable luminous intensities: here, unequally distributed intensities of heat; there, chemical combinations and decompositions. Only, the ray, which is endowed with considerable calorific and chemical power, does not excite in us the luminous sensation, or rather, only exercises on our retina an inappreciable influence. Thus, as there are sounds in Nature to which our ears are not attuned, so are there colours in the spectrum which will for ever remain invisible to us.

CHAPTER XI.

PHOSPHORESCENCE.

Phenomena of spontaneous phosphorescence—Animal and vegetable phosphorescence—Glow-worms and fulguræ; infusoria and medusæ—Different conditions which determine the phosphorescence of bodies—Phosphorescence by insolation—Becquerel's phosphoroscope.

WE have already alluded to fluorescence; there is another curious phenomenon which differs from fluorescence in this, that it remains for long after the exciting source of light is withdrawn. The history of the discovery of phosphorescence is as follows:—

In 1677, an alchemist of Hamburg, named Brandt, discovered by a process which he at first kept secret,[1] a new body endowed, among other singular properties, with the property of emitting a continuous luminous smoke when it was exposed to the air. Hence the name phosphorus (from φῶς, light; φέρω, to bear) applied to this substance, which is one of the sixty-six simple bodies now recognized. If we trace characters on a wall with a stick of phosphorus, they will appear as luminous lines in the dark, and will not cease to shine until after the complete disappearance, either by slow combustion or evaporation, of the phosphorescent matter.

Long before the discovery of this body, the name of phosphori was given to all substances which, like it, emitted light without being accompanied by sensible heat; such as wood, decomposed by the action of moisture; dead salt-water fish not yet putrified, the shining of which is communicated to the water itself, when it is agitated for some time; and lastly, a great number of mineral substances, when they are submitted to blows or to mechanical friction, or when they have been exposed to the solar rays.

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[1] A few years after Brandt, Kunckel discovered the means of obtaining phosphorus. A century later, in 1769, Scheele proved that it exists in abundance in the bones of men and animals.

It is to this emission of spontaneous or artificial light that physicists have given the name of *phosphorescence*. Phosphorescence is not peculiar to inorganic or lifeless matter. When, on a warm evening in June or July, we walk in the country, it is not uncommon to see in the grass and under the bushes a multitude of small lights, which shine like terrestial stars: these are the lampyres, or glow-worms, a species of coleoptera, the larvæ of which, like the perfect insect, but in a less degree, possess the property of emitting a greenish blue light. The fulgora or lantern fly, and the cucuyos of Mexico aud Brazil, shine during the night with a light sufficiently bright to enable one to read. Certain flowers, like the flowers of the marigold, nasturtium, and Indian rose, have been considered as phosphorescent, but it now appears to be proved that this is a mistake; it is certain that fifteen phanerogamic plants, and eight or nine cryptogamic ones, emit light; but only in the evening after they have been receiving the sun's light; so that exposure to the sun appears to be to them a condition essential to phosphorescence. The phosphorescence of the sea is produced by myriads of animalculæ, which, like the lampyres and fulgoræ, emit a light sufficiently bright to give to the waves the appearance of fire. It is now infusoria, now medusæ, starfishes, &c., which diffuse, some a blue, others red or green lights, or even give the sea a whitish tint, to which sailors give the name of sea of snow or sea of milk.

Calcined oyster-shells become luminous when they are exposed to the light of the sun: this property is due to the sulphide of calcium; it is also possessed by the sulphides of barium and strontium.[1]

Phosphorescence can be induced in a great many substances by mechanical or chemical action; this may be noticed on breaking sugar, the light being produced at the moment of rupture.

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[1] Canton, an English physicist, discovered in 1764 the phosphorescence of calcined oyster-shells ; hence the sulphide of calcium is called Canton's phosphorus. V. Calciarolo, a workman of Bologna, discovered the phosphorescence of calcined sulphate of baryta hence the name Bologna phosphorus which is given to sulphate of barium.

Similar effects are produced by rubbing two pieces of quartz against each other, also chalk, or chloride of calcium, or on separating plates of mica by cleavage. Elevation of temperature also produces phosphorescence. Fluorspar, diamonds and other precious stones, chalk, sulphate of potassium and quinine, emit light when they are placed in contact with warm substances. We shall see further on, that electricity is able to produce the same effects in bodies which are bad conductors.

Thus we have a series of phenomena in which the production of light is neither the result of rapid combustion at a high temperature, nor that of a vivid illumination which disappears as soon as the source ceases to be in the presence of the illumined object. All the bodies which we have mentioned, and which peculiar circumstances render phosphorescent, acquire, for a limited, but often considerable time, the property of being luminous by themselves, of emitting light perceptible in the dark, and strong enough to illuminate objects lying near them.

Phosphorescence appears to be due to multiple causes: in organized and living beings, the mode of producing light is nearly unknown. We only know that the will of the animal plays a certain part, that a moderate temperature is necessary to the emission of the light, as also is the presence of oxygen gas. A sharp cold or intense heat both cause it to disappear. In phosphorus, decayed wood, dead fish, &c., the production of light is doubtless due to chemical action,—that is, to slow combustion; for, *in vacuo*, all phosphorescence ceases. It follows, therefore, from the facts above stated, that exposure to the sun, elevation of temperature, electricity, and mechanical action, in which electricity and heat doubtless take part, are, in many cases, favourable conditions to the development of phosphorescence. This singular mode of production of light has recently been the subject of very interesting studies, by MM. Biot, Matteucci, and principally by M. Edmond Becquerel. We will rapidly glance at some of these.

It has long been known that phosphorescence is a property which can be momentarily acquired by a number of bodies, especially in a solid or gaseous state: paper, amber, silk, and a multitude of other substances of organic origin; oxides and salts of alkaline and earthy metals, and of uranium; and a great many gases. But no other metals, nor their compounds, nor any other kind of liquid, has up to the present time manifested the slightest trace of this phenomenon.

The tints of phosphorescent light vary according to the nature of the body which emits it: thus precious stones emit a yellow or blue light; sulphides of strontium, barium, and calcium give all the shades of the spectrum, from red to violet. But a singular fact proved by M. Ed. Becquerel is that the tint and brightness of the light do not depend alone on the temperature, but also on the mode of producing the sulphides, and, what is still more singular, on the molecular state of the salts whence they have been produced. Thus, having taken different carbonates of lime, spar, chalk, &c., and having treated them with sulphur, he obtained six sulphides of calcium which, exposed to the sun, became phosphorescent, and in darkness presented the following tints:—

		Tint of the Light.
Sulphides of Calcium obtained from	Iceland spar	Orange yellow.
	Chalk	Yellow.
	Lime	Green.
	Fibrous arragonite	Green.
	Marble	Rose violet.
	Arragonite of Vertaison . .	Rose violet.

"If I may be allowed the comparison," says M. Edmond Becquerel, in regard to these facts, "I could say that these last bodies, on account of their luminous effects, are analogous to the sonorous cords which produce different sounds according to their tension."

Elevation of temperature accelerates phosphorescence, but it also exhausts it quickly: for the light obtained does not last long. It has also the effect of modifying the tints; thus sulphide of strontium, blue at the ordinary temperature, passes to a blue violet, clear blue, green, yellow, and lastly to orange, when its temperature is raised from 20 degrees below zero to 150 degrees above.

It will be of much interest to study the manner in which the different rays of the spectrum act on bodies in determining their phosphorescence, from the chemical rays situated in the dark part of the spectrum beyond the violet, to the heat-rays beyond the red. In order to observe this, the spectrum is projected on band covered with various phosphorescent substances, and the luminous effects produced are examined in the dark at different distances; that is to say, in the regions covered by the prismatic rays. Thus, it is possible to ascertain which of the rays produce the most intense luminous effects. It is found that the maximum of action depends on the bodies influenced; but in every case, the chemical rays nearest the violet, and consequently the most refrangible, produce phosphorescence: the heat-rays do not excite it; but they are endowed with the property of continuing the action of the chemical rays. These results explain the feeble action of the flame of candles, or gas, in producing the phosphorescence of bodies, and, on the other hand, the efficiency of the electric light: this latter abounds in chemical and ultra-violet rays, whilst the former, although rich in heat-rays, are very poor in chemical rays. The bright light of magnesium rivals, as M. Le Rorey proves, the electric light. It is sufficient to burn a wire

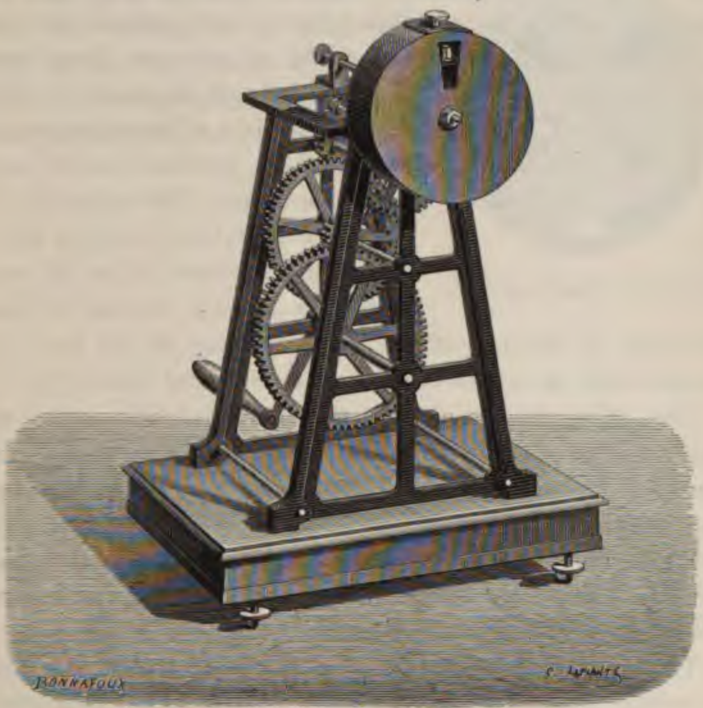

FIG. 242.—M. Ed. Becquerel's phosphoroscope.

of this metal in presence of a tube enclosing, for example, some sulphite of calcium, to obtain prolonged phosphorescence, as may be shown by carrying the tube into darkness.

M. Edmond Becquerel invented, for the study of these phenomena, an instrument which he calls the *phosphoroscope*. The following is a short description of it:—Two blackened discs are each pierced with four openings in the form of sectors, and can be caused to revolve on a common axis; but as the openings of one do not correspond with the openings of the other (as may be seen in Fig. 243), it follows that a ray of light cannot pass through the system of the two discs, whatever may be the rate of rotation. They are both enclosed in a blackened box, which remains fixed, and in the sides of which are two openings. The solar light passes through one of them, falls on the body, the phosphorescence of which is to be studied, and which is fixed between the two discs, in the axis of the outer openings of the box; but, as we have said, it cannot pass through the other side.

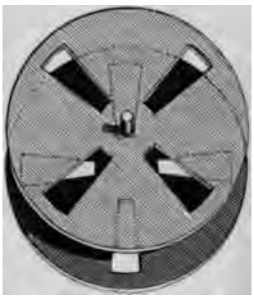

FIG. 243.—Disc of the phosphoroscope.

The phosphorescent light induced in the body passes, on the contrary, through the opposite opening every time the rotatory movement brings one of the moveable windows in front of the outer opening. The action of light on the body is thus produced four times during each revolution. If the velocity is sufficient, the developed phosphorescence is continuous, and the sensation produced in the eye of the observer is equally so.

The phosphoroscope, thus constructed, gives to the body observed a constant quantity of light, whatever the rotatory movement may be; the quantity of phosphorescent light which reaches the eye is also constant; but the duration of the constant action of the light on the body varies with the velocity, as it is equal to the time that an opening takes to pass before it: this duration is easily measured when one knows the dimensions of the opening and the number of turns that the system of the two moveable discs makes in one second. To sum up: the more rapid the rotation, the shorter the duration of the light, but the interruptions in this action are shorter, so that there ought to be a certain velocity for which the maximum brilliancy is obtained.

By the aid of the phosphoroscope, M. Becquerel, besides the result we have already described, has been able to prove the existence in some bodies of luminous emissions, the duration of which does not exceed the ten-thousandth part of a second. Others, like the green sulphide of strontium and calcium, remain phosphorescent for thirty-six hours. Diamonds shine for many hours. He has been able to study the law according to which the phosphorescent bodies lose their light by successive emissions.

The light emitted by various vegetable and animal phosphorescents has been submitted to spectrum analysis; and it is found that the spectra of these lights are continuous, as neither dark nor bright lines can be distinguished.

CHAPTER XII.

WHAT IS LIGHT?

Hypotheses concerning the nature of light—Newton's, emission theory—Huyghens', undulatory theory; vibrations of the ether—Propagation of luminous waves: wave-lengths of the different rays of the spectrum.

HITHERTO we have described luminous phenomena as studied by observation, without indicating any hypothesis regarding the particular nature of the agent which induces the perception of these phenomena by our organs. All that we know is, that the various substances in Nature can be ranked in two classes: in the first are placed light-sources, or bodies capable of producing light directly and of themselves; in the second, bodies which transmit in divers ways the light falling on them, but which, in their actual state, cannot directly emit it.

Among light-sources, there are some, like the sun and most of the stars, which appear to be constant,—at least their emissive power has not decreased for thousands of years: probably we ought to count by millions of centuries, if we wish to measure the probable duration of this power. But they doubtless do not differ essentially from temporary luminous sources which we have at our disposal on the surface of the globe. These latter owe their state either to a very high temperature, to chemical combinations conducive to the disengagement of light, such as a furnace, or to a state of electric tension producing the same result—take the electric light. All that we know of the physical constitution of the sun, and say, a white-hot cannon-ball or any mass of metal, tends to prove that they are globes in a state of incandescence. We have already seen that, among the substances of the second class, there are many which can momentarily acquire, under the influence of temperature, exposure to the sun, or certain chemical or mechanical actions, the property of emitting light, which is called phosphorescence; and that without being in a state of incandescence or vivid combustion.

We know also that light is not transmitted instantaneously, but that it requires a definite time to pass from one point to another—in a word, that it has a particular mode of movement. We have now, therefore, to inquire in what this movement consists; that is, whether light is a substance incessantly emitted by luminous bodies, or an impulse produced in a special medium, and propagated through space. These are questions of such great interest, that they necessarily force themselves upon the mind; their examination will also have the advantage of furnishing us with an explanation of various phenomena to be hereafter described. The time has therefore arrived for us to indicate the nature of a theory now generally received by physicists, and by the help of which all optical phenomena are found to be consequences of a single principle. At the same time, we may give certain details concerning another hypothesis, which for a length of time had the privilege to share with the first a common applicability to optical phenomena. We will first consider the older theory, known as the emission theory.

According to Newton, who first reduced this theory to a system, light is formed of material molecules of extreme tenuity, which are perpetually emitted by luminous bodies, and which the latter project through space with a uniform velocity; the impact of these projectiles on the retina agitates the optic nerves, and produces in us the sensation of light. These particles are endowed with attractive and repulsive forces, which are manifested in the neighbourhood of the molecules of bodies, and produce the attractive forces of interior refraction and reflection, and the repulsive forces of exterior reflection. There are as many kinds of particles as colours, and each kind possesses a particular refrangibility.

Successive particles which follow the same right line form a luminous ray; but they may be separated by great intervals. The luminous impression has been proved to remain on the retina about one-tenth of a second; it is therefore sufficient that ten luminous particles should arrive at the eye in a second, in order that the impression caused by one of them is not effaced before the arrival of the next; or, which is the same, in order that there shall be a continuous sensation. Supposing them situated at equal distances, they should follow each other at a distance of 29,800 kilometres from each other. Supposing they follow each other at the rate of a hundred a second, there would still be an interval between them of 2,980 kilometres.

We understand, therefore, how, according to this hypothesis, the luminous rays emanating from different sources can intersect each other in various directions without obstruction. But we must suppose the mass of each of them is of such small weight, that our imagination can scarcely realize the idea. Of this Sir J. Herschel made the following comparison. He says: "If a molecule of light weighed one grain (0·065 gramme), its effect would be equal to that of a cannon-ball of 150 lb. (56 kilogrammes), animated by a velocity of 305 metres per second. What, then, must this tenuity be, if a thousand million of molecules, attracted by lenses and mirrors, have never been able to communicate the least movement to the most delicate instruments invented expressly for these experiments!" (*Treatise on Light*, vol. i.)

We have just stated that, to explain the phenomena of reflection and refraction of light, Newton imagined that each molecule is either repelled or attracted by the molecules of bodies. The intensity of these forces, which are exerted in infinitely small spheres, is prodigious; it is proved that they exceed the intensity of gravity at the surface of the earth to such a degree, that it is necessary, in order to express their value in numbers, to multiply this latter intensity by the figure 2, followed by forty-four zeros.

In the theory which is now adopted,—the undulatory theory,—we find numbers which submit somewhat to precedent; it is not difficult, therefore, to conceive that it has been preferred to the theory of emission.

We owe the first exact exposition of the undulatory theory to Huyghens, who numbered among his partisans, in the last centuries, Hooke and Euler; and among those who have developed and perfected it in the present century, Young and Fresnel. We will endeavour to explain the undulatory theory in its essential elements.

The hypothesis of emission requires that the interplanetary celestial spaces be void of matter, in order to give free passage to the motion of the luminous molecules, or rather these spaces must be free from all matter, save the molecules themselves. On the other hand, according to the undulatory hypothesis, these same spaces are filled with an extremely thin and eminently elastic fluid, which is called the ether. This medium penetrates all bodies, and is diffused throughout all their inter-molecular spaces.

Luminous bodies are those whose molecules, in a state of continual vibration, communicate impulses to the ether, which, in its turn, propagates the same vibratory movement from place to place and in all directions, with a uniform velocity of 298,000 kilometres per second. The velocity of propagation of the luminous waves is the same for all the rays of light, whatever their intensity or colour. It is uniform and constant in a homogeneous medium; but it varies in passing from one medium to another; and, as it is admitted that it is dependent on the connection which exists between the elasticity of the ether and its density, it must be inferred that this connection itself changes in different media; that is to say, the distribution of the molecules of ether is not the same in interplanetary media as in heavy bodies; and in these it varies with the nature of the substances and their density.

Let us try to understand the nature of the vibrations of the ether.

Each molecule of a luminous source executes a series of very rapid vibrations; that is to say, of backward and forward movements across a position of equilibrium. These vibrations are communicated to the ether, the different molecules of which assume the vibratory movements similar to those of the light source, and communicate them spherically from place to place. During the time which a molecule of ether requires to make a complete oscillation round its position of equilibrium, its movement is communicated, in the direction of the propagation of light, to a stream of molecules, the most distant of which is at a fixed distance from the first: it is this distance which is called the wave-length, and the luminous wave is nothing more than the series of movements effected during a complete oscillation of a molecule of ether. As the same disturbance which has its origin at one point of the source of light is thus propagated in the ether which fills space, with uniform velocity, it follows that all points of the surface of a sphere, having for its centre the luminous point, is at the same instant in the same phase of vibratory movement. All the points of any of these spherical surfaces are called the surface of the wave. In certain media, the surface of the wave can be ellipsoidal. Luminous waves have, therefore, great analogy with sonorous waves; like them, they are isochronous, and they move with uniform velocity. They consist in alternating movements of an elastic medium across a position of equilibrium; but, whilst the vehicle of sound is a tangible medium, as the air, or any other gaseous or liquid or solid body, the vehicle of light is a substance, if not imponderable, at least intangible.

The sonorous wave is propagated through the air, travelling in a right line 330·6 metres per second; the luminous wave, in the same time, travels 186,000 miles, and, whilst the length of an undulation varies, for perceptible sounds, between five millimetres and ten metres, the maximum length of an undulation of ether does not attain the thousandth part of a millimetre. But between these two modes of vibratory movement there exists, as Fresnel has shown, an important difference; for, whilst sonorous vibrations are made in the same direction as their propagation, luminous vibrations take place in a direction perpendicular to that of the movement of propagation, that is, parallel to the surface of the waves. It is difficult to imagine the vibrations being effected perpendicularly to the direction of their propagation. A comparison will explain this kind of movement. If we take hold of the end of a very long cord placed in a straight line along the ground, and give it a shake in a vertical direction, there follows a series of undulations which are propagated to the other extremity, all of which are effected in a direction perpendicular to that of the cord, just as we see undulations which succeed each other on the surface of the water caused by the throw of a stone, or any other heavy body, on the liquid. There is, between these two phenomena and the movement of the ether, one resemblance more; that is, that the propagation of the waves takes place without their being any transport of the molecules which undergo the vibration.

We shall presently understand how the wave-lengths of luminous vibrations can be measured, and how it was discovered that these lengths vary in passing from one colour to another. They are, as the following table shows, excessively small, their mean value scarcely

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ever exceeding the half of a thousandth of a millimetre. When these wave-lengths are once known, an easy calculation gives the number of vibrations which the ether performs in a second, when it gives rise to the different colours of the spectrum. As light travels over an interval of 298,000 kilometres in one second, it is sufficient to divide this last number by each wave-length, in order to find how many of these vibrations take place in a second.

Here are the results for the seven principal colours of the solar spectrum:—

		Lengths of Waves in millionths of a millimetre.	Number of vibrations per second.
Red,	mean	620	514,000,000,000,000
Orange,	„	583	557,000,000,000,000
Yellow,	„	551	548,000,000,000,000
Green,	„	512	621,000,000,000,000
Blue,	„	475	670,000,000,000,000
Indigo,	„	449	709,000,000,000,000
Violet,	„	423	752,000,000,000,000 [1]

This determination of wave-lengths, combined with wide dispersion, enables us, by reason of the high velocity of some of the motions of the heavenly bodies,—a velocity comparable with that of light itself,—and the existence of bright and dark lines in the spectra, to determine the rapidity of the various movements.

Let us endeavour to give an idea how this result is arrived at, begging indulgence for a gross illustration of one of the most supremely delicate of nature's operations.

Imagine a barrack, out of which is constantly issuing with measured tread and military precision an infinite number of soldiers in single or Indian file; and suppose yourself in a street seeing these soldiers pass. You stand still, and take out your watch, and find that so many pass you in a second or minute, and that the number of soldiers, as well as the interval between them, is always the same.

You now move slowly towards the barrack, still noting what happens. You find that more soldiers pass you than before in the same time, and, reckoned in time, the interval between each soldier is less.

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[1] These numbers are deduced from the new determination of the velocity of light; they exceed by about $\frac{1}{30}$ those given in treatises on physics before the result of M. Foucault's experiments was known.

You now move still slowly from the barrack, *i.e.* with the soldiers. You find that fewer soldiers now pass you, and that the interval between each is longer.

Now suppose yourself at rest, and suppose the barrack to have a motion, now towards you, now from you.

In the first case the men will be paid out, so to speak, more rapidly. The motion of the barrack-gate towards you will plant each soldier nearer the preceding one than he would have been if the barrack had remained at rest. The soldiers will really be nearer together.

In the second case it is obvious that the interval will be greater, and the soldiers will really be further apart.

So that, generally, representing the interval between each soldier by an elastic cord, if the barrack and the eye approach each other by the motion of either, the cord will contract; in the case of recession, the cord will stretch.

Now let the barrack represent the hydrogen in Sirius or the sun, perpetually paying out waves of light, and let the elastic cord represent one of these waves; its length will be changed if the hydrogen and the eye approach each other by the motion of either.

Particular wave-lengths with the normal velocity of light are represented to us by different colours.

The long waves are red.

The short waves are violet.

Now let us take the case of the hydrogen in the sun and fix our attention on the green wave, the refrangibility of which is indicated by the F line of hydrogen. If any change of wave-length is observed in this line, *and not in the adjacent ones,* it is clear that it is not to the motion of the earth or sun, but to that of the hydrogen itself and alone, that the change must be ascribed.

If the hydrogen is approaching us, *the waves will be crushed together;* they will therefore be shortened, and the light will incline towards the violet, that is, towards the light with the shortest waves; and if the waves are shortened only by the $\frac{1}{10000000}$th of a millimetre, we can detect the motion.

If the hydrogen is receding from us, the waves will be drawn out; they will therefore be longer, and the green ray will incline towards the red.

In Sirius there is hydrogen, and by this means Mr. Huggins has determined the velocity of that star's movement in the heavens.

Now, in the case of the sun, bear in mind that there are two different circumstances under which the hydrogen may approach or recede from the eye.

Take a globe which we will consider to represent the sun. Fix your attention on the *centre* of this globe: it is evident that an uprush or a downrush is necessary to cause any alteration of wave-length. A cyclone or lateral movement of any kind is powerless; there will be no motion to or from the eye, but only at right angles to the line of sight.

Next fix your attention on the edge of the globe—the limb, in astronomical language: here it is evident that an upward or downward movement is as powerless to alter the wave-length as a lateral movement was in the other case, but that, should any lateral or cyclonic movement occur here of sufficient velocity, it might be detected.

So that we have the centre of the disc for studying upward and downward movements, and the limb for studying lateral or cyclonic movements, if they exist.

Now the hydrogen lines in the solar spectrum are observed to change their places, *while the lines near them remain at rest,* so that they may be looked upon as so many milestones telling us with what rapidity the uprush and downrush takes place; for the twistings in the hydrogen lines are nothing more or less than alterations of wave-length, and thanks to Ångström's map we can map out distances along the spectrum from F in $\frac{1}{10000000}$ths of a millimetre from the centre of that line; and we know that an alteration of that line $\frac{1}{10000000}$ths of a millimetre towards the violet means a velocity of 38 miles a second towards the eye, *i.e.* an uprush; and that a similar alteration towards the red means a similar velocity from the eye, *i.e.* a downrush.

To sum up: these are the two theories proposed for the explanation of luminous phenomena. Both explain with equal facility the reflection and refraction of light; but, whilst the system of emission requires that the velocity of propagation be greater in refractive upset all the ideas then conceived as to the nature of this luminous agent. And, indeed, it seemed to show, *that light added to light produces, in certain cases,* DARKNESS !

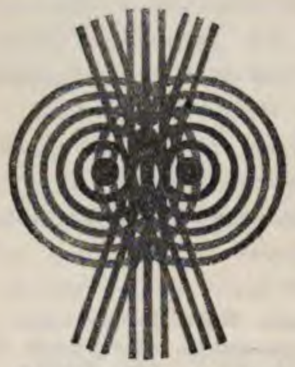

FIG. 244.—Grimaldi's experiment. Dark and bright fringes produced by a system of two small circular holes.

Newton studied the phenomena of diffraction discovered by Grimaldi; and he added fresh observations, and endeavoured to explain the cause of diffraction by a deviation when the edges of opaque bodies are subjected to the rays of light. Fraunhofer, Young, and Fresnel succeeded in discovering the laws, and the last-named connected them in the most happy manner with the undulatory theory. Before continuing the description of the phenomena, let us endeavour to form some idea of what Young called the principle of interference—a principle the theory of which he has clearly explained on the undulatory theory, and which Fresnel afterwards demonstrated by the famous experiment of the two mirrors.

Let us suppose that two rays of light follow the same direction, A B; that they have the same intensity, and that the wave-lengths of each of them are equal, in which case the vibratory movements of the ether will have the same amplitude for the same phases. If the waves of the first ray coincide with those of the second, it is clear that their intensities will become united; the quantity of light will be increased by their union. But if one of them is behindhand precisely half the length of a wave, the molecules of ether situated along the line A B will be drawn from one side by forces the intensity

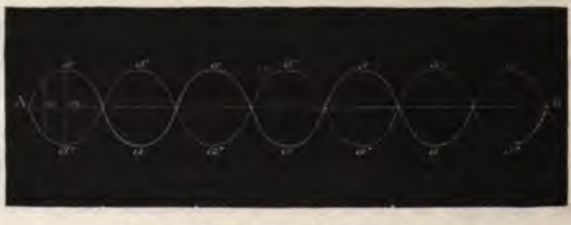

FIG. 245.—Interference of luminous waves.

and direction of which will be represented by the curve *a a a* . . . . and from the other side by equal and contrary forces represented by the curve *a′ a′ a′*. . . . Every molecule, such as *m*, will then remain at rest under the action of these opposed forces: the vibratory movement will cease, and darkness will succeed to light. It is then said that the luminous waves or rays interfere.

The same result is produced if the retardation is $\frac{3}{2}$, $\frac{5}{2}$ . . . and generally, odd numbers of half undulations. If it be an even number of half undulations, the result is the same as if there had been coincidence. Thus, between these two extreme cases, the luminous intensity is sometimes increased and sometimes diminished, but in neither case is there an absolute destruction of light.

Theoretically, this reasoning, which is a necessary consequence of the undulatory theory, perfectly accounts for Grimaldi's experiment, and all those in which dark and bright fringes or bands appear. It nevertheless had to be proved by observation, and this Fresnel accomplished, mainly by the experiment of the two mirrors we have already mentioned. This experiment is too important for us to neglect here. The nature and limits of this work do not permit us to touch upon theoretical explanations of many phenomena, but the principle in this instance must at least be described with sufficient clearness to enable the reader to accept the inferences with confidence.

Two plane mirrors, O N, O M (Fig. 246), of metal or black glass, are placed vertically in a dark room, so as to form a very obtuse angle. In front of these mirrors a beam of sunlight is brought to a focus at S by a spherical or cylindrical lens, so that it can give either a point or a luminous line. Two images are thus formed, one in each mirror; that in *s* for the mirror O N, the other in *s′* for the mirror O M.

We have thus two sources of light which present this peculiarity, that, as they emanate from a common source, they are in the same state of vibration. If we now place a vertical screen in front of the mirrors, in such a way as to receive the luminous beams from the two images, a bright band will be perceived on the screen in the prolongation of the line O A, and, on each side of this band, a series of alternate dark and bright fringes. If one of the mirrors is taken away, the fringes instantly disappear, and the screen is equally illuminated.

It is thus seen that the phenomenon is the same as in Grimaldi's experiment of the two openings, and it remains for us to explain how light added to light can produce darkness ; or, as we have seen, that whenever dark fringes occur, it is due to the interference of luminous waves emanating from two sources, and that, on the other hand, we have the same phase of undulation whenever bright fringes or bands are seen. Figure 246, in which we observe concentric waves emanating from *s* and *s'*, demonstrates this. These two systems of waves cross and cut each other at different points. Now, such of these points which, like *a*, are situated on the perpendicular A O and *s s'*, are in the same phase of undulation in both systems, since the rays *s a*, *s' a*, being of the same length, the same paths S I *a* and S I' *a* are followed by the two luminous waves emitted

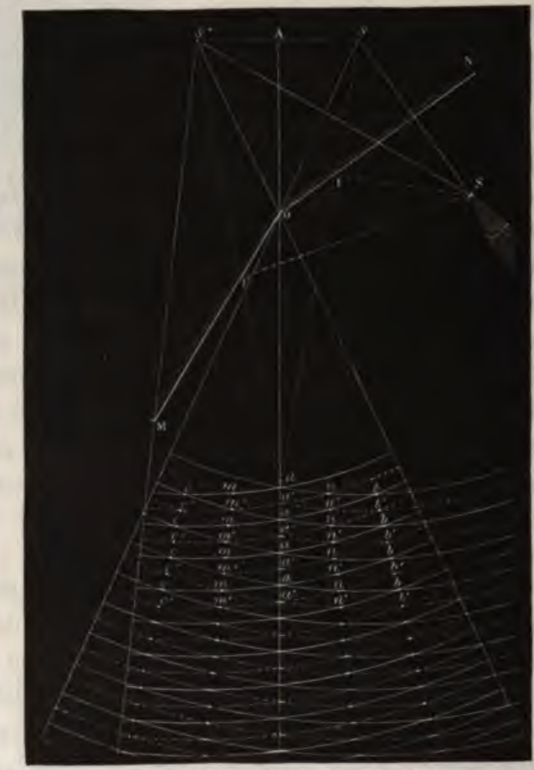

FIG. 246.—Fresnel's experiment of two mirrors ; experimental demonstration of the principles of interference.

from the source S, and reflected by both mirrors. The same takes place with regard to the points a' a a' . . . situated in the vertical plane passing through A O.

The luminous intensities are therefore united in this plane; hence the central bright fringes. In positions such as n, n', the difference of path of the waves which cross each other is from $\frac{1}{2}$, $\frac{3}{2}$ . . . wave-lengths; in other words, an odd number of half undulations: hence interference ensues, and consequently a dark band. It is so also for the points m m'. . . . Further on, the points b b' . . . c c' . . . belong to rays each of which is delayed an even number of half wave-lengths behind the other; hence bright fringes . . . and so on.

In order to try this admirable experiment, Fresnel used in succession lights of all the simple colours; he found fringes of each of these tints, but they became narrower as he got farther from the red in the series of prismatic colours. Violet gave the narrowest bands. By measuring with great precision the distances of the bands, this illustrious physicist succeeded in deducing the wave-lengths of light of different colours, and afterwards the number of vibrations executed by the ether in the short interval of a second—the wonderful numbers we have already seen. Fringes proceeding from white light ought therefore to be formed of fringes coloured by each of the spectral tints superposed upon each other, so that the violet would be by the side of the central bright band. Observation proves this. Thus, by this memorable experiment the truth of the undulatory theory is confirmed; mathematical analysis has also drawn from it a crowd of inferences, some already known by observation, others outstripping observation and serving as a guide to it. The names of Huyghens, Young, and Fresnel will remain for ever attached to this beautiful theory, as is that of Newton to the theory of universal gravitation.

Let us now return to the phenomena of diffraction, all of which relate to the principle of interference of luminous waves. They are so numerous that we can only choose some of the most remarkable.

Newton, while repeating and varying Grimaldi's experiments on the enlarged shadows of fine bodies, such as hair, thread, pins, and straws, became convinced that the deviation of the luminous rays was not due, as was at first believed, to a refraction in a thin stratum of denser air surrounding the bodies. He saw also that the formation of fringes did not depend on the nature of the substances used. Whether metals, stones, glass, wood, or ice, &c. were used, he always recognized three fringes succeeding each other and starting from the shadow. The interior fringe was violet, deep blue, light blue, green, yellow, and red; the exterior one, pale blue, pale yellow, and red. He also observed that monochromatic lights produce fringes of unequal width. But all his experiments led him to the conclusion, that the rays of light undergo, in passing by the edges of a body, inflections which are stronger the nearer they graze the surface. This was a natural hypothesis, in accordance with the emissive theory; but we shall presently understand the true explanation.

The very numerous experiments which have been since performed in connection with this subject, may be arranged under two heads. The first comprises phenomena of diffraction produced by rectilinear edges; for instance, by one or by several very narrow slits, in the form of parallelograms, or by a very fine screen, a metallic thread, or a hair: the second comprises phenomena obtained when the diffraction is produced by means of one or more extremely small apertures, either square, triangular, circular, or by the edge of a circular screen of small dimensions. Plates V. and VI. represent systems of fringes produced under these varied circumstances: some, coloured, proceed from white light; others, monochromatic, from light of a single colour,—for instance, red light. We see, in many cases, fringes accompanied by a multitude of small spectra, the bright colours of which add to the beauty of the phenomenon.

Sir J. Herschel observed curious diffraction effects by placing in front of the object-glass of an astronomical telescope diaphragms of different forms, and then observing single and double stars. With an annular opening, he saw coloured rings surrounding the images of luminous points, which then presented discs similar to those of the planets. Triangular diaphragms gave, on the contrary, stars with six rays; an aperture formed by twelve concentric squares gave a star with four rays. Lastly, by piercing in a regular manner equilateral triangles on the diaphragm, he obtained a series of circular discs, arranged on six lines, on which they diverged, starting from a central colourless and very bright disc; they were, more-

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over, each surrounded by a ring more or less coloured, and spread into spectra as they extended farther from the centre.

These phenomena are of great interest; the magnificent colours which are presented to the eye form, as it were, so many pictures, the variety of which equals their splendour. But to the eyes of the physicist they present still greater interest, inasmuch as they are so many confirmations of the beautiful theory of the undulations of the ether. Mathematical analysis applied to the different phenomena of diffraction produces results which agree, in a marvellous manner, with those of observation. We have already said that they sometimes outstrip it, and of this the following is a remarkable example.

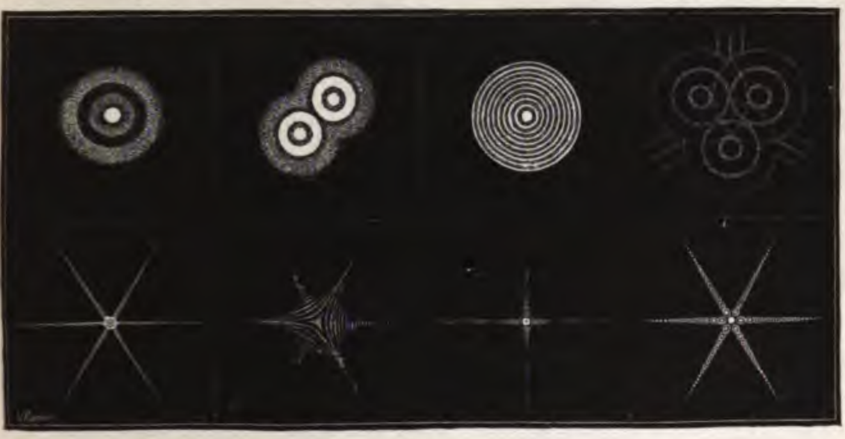


FIG. 247.—Effects of diffraction in telescopes. (Sir J. Herschel.

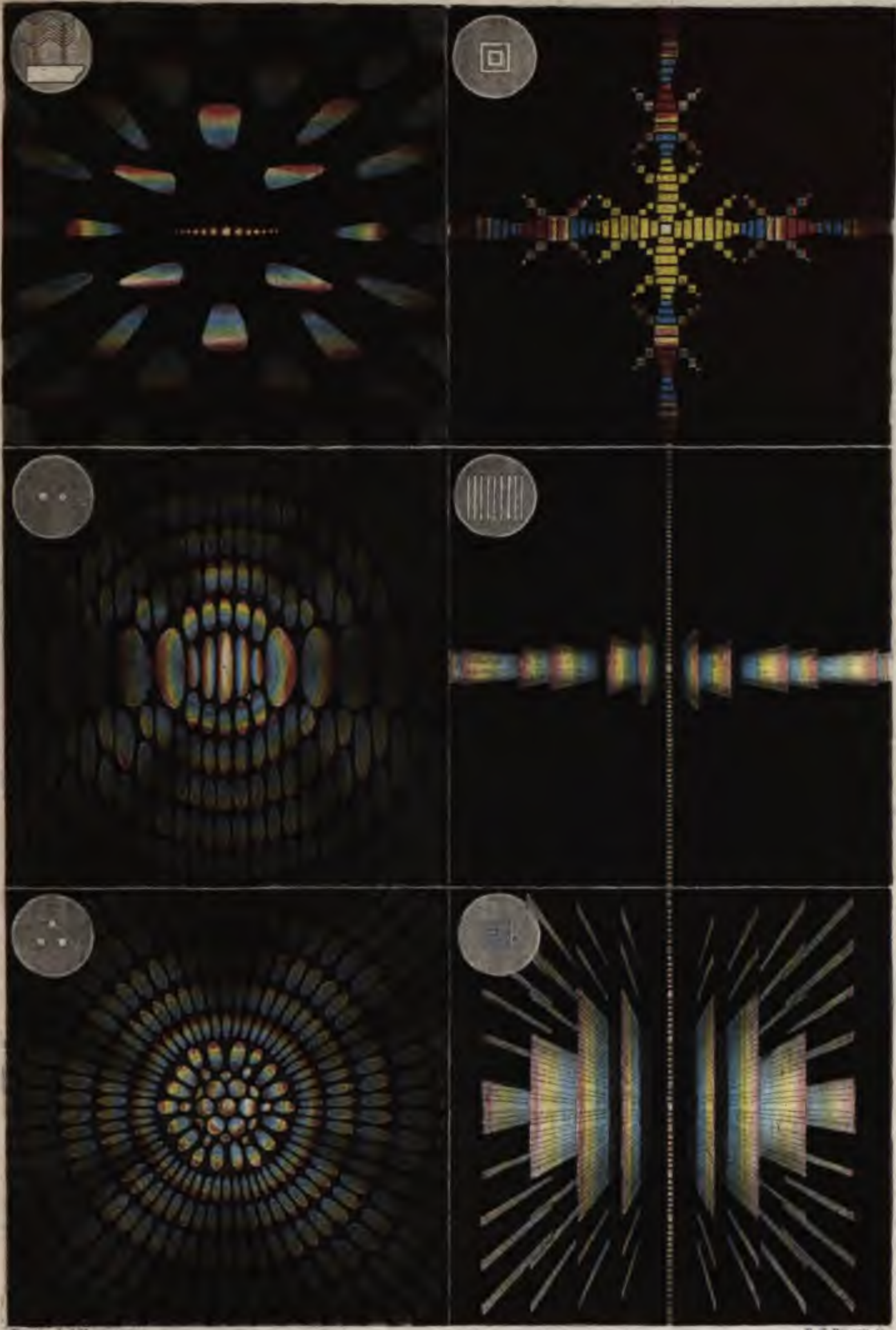
The geometer Poisson, having submitted to calculation the problem which has for its object the determination of the nature of the shadow and the fringes produced by an extremely small opaque disc exposed to the light which diverges from a luminous point, found that the centre of the shadow ought to be as brilliant as if the disc did not exist: this light was an effect resulting from the diffraction of luminous waves on the edge of the screen. Such a result was so opposite to preceding observations, that Poisson presented it as a serious objection to the undulatory theory. But Arago having made the experiment with requisite care, by using a very small metal disc cemented on a diaphanous and perfectly homogeneous glass plate, found that the luminous point appeared as calculation had indicated. It was as if the shadow was produced by a screen pierced at the centre. This experiment evidently affords one of the most beautiful triumphs of the theory,—a decisive proof in favour of the undulatory theory of light and of the existence of the ether.

Fraunhofer, whose beautiful experiments on the lines of the spectrum we have already described, introduced into the study of the phenomena of diffraction, the excessive precision which so eminently distinguished him. After having observed the images produced by a very limited number of small openings, he conceived the idea of examining the effect produced when light traverses a grating formed of a multitude of very fine threads either parallel or crossed. He first used a grating of brass wire, composed of numerous very fine wires, stretched on a rectangular frame by means of screws suitably arranged. Then, to obtain a greater regularity and delicacy in the intervals through which the light passed, he traced parallel and equidistant lines on plates of glass covered with gold leaf; then engraved them with diamonds on the glass itself, thus forming more than 1,000 divisions per millimetre. Each of the striæ is an opaque screen, and the interstices left by the striæ allowed the light to pass through. However, a much smaller number of divisions makes the grating more regular, and thirty-eight lines in a millimetre are sufficient to show the phenomena.

Beside the parallel-line grating, Fraunhofer studied gratings with square meshes, formed by two series of lines crossing each other at right angles; also those of circular and other forms of mesh. In this manner he obtained a number of figures, in which the fringes and spectra are distributed with wonderful symmetry; but he did more, he studied the laws of this distribution—laws which M. Babinet has proved to be necessary consequences of the principles of interference.

Plate VI. shows the phenomena resulting from the passage of light through a grating with parallel lines: at the centre is a bright line, then two rich dark intervals followed on each side by two spectra—the violet of which is nearest the centre, and so pure that the dark lines are easily distinguished. Beyond this there are two fresh dark bands, and lastly, two series of superposed spectra, paler and more and more extended. A grating with square meshes gives the image represented in the same Plate VI. below the preceding

PLATE VI.



D'après J. Silbermann.

R. H. Digeon sc.

POLYCHROMATIC FRINGES

Interference Phenomena

DIFFRACTION PRODUCED BY GRATINGS.

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one: besides the bright central line and two series of spectra more extended than those of the grating with parallel meshes, we see in the four right angles a multitude of small spectra radiating towards the centre. Newton had a glimpse of the phenomena of diffraction through small apertures and gratings, as the following passage in his "Optics" shows: "On looking at the sun through a piece of black ribbon, held close to the eyes, we perceive several rainbows; because the shadows which the fibres or threads throw on the retina are edged like coloured fringes." Figure 1, Plate VI., represents the effect produced by the diffraction of solar light through the grating formed by the broad part of a bird's feather. Fringes of a like nature can be equally observed by the light of a candle, with the eyes nearly closed; the lashes, on joining, then form meshes of irregular form.

It is by the interference of luminous rays that physicists explain the bright colours which are noticed on certain bodies whose surfaces are covered with a multitude of very fine striæ: the feathers of several birds, and the surface of mother-of-pearl, for instance, are formed of numerous striæ which reflect all the prismatic colours. Brewster, having occasion to fix mother-of-pearl to a goniometer with a cement of resin and wax, was greatly surprised to see the surface of the wax bright with the prismatic colours of the pearl: he repeated the experiment with different substances,—realgar, fusible metals, lead, tin, isinglass,—and in each case he saw the same colours appear. An Englishman, Mr. John Barton, applied this property of striated surfaces to the arts; he worked very fine facets on steel buttons and other objects which, in the light of the sun, gas, or candles, exhibit designs brilliant with all the colours of the spectrum. "These colours," says Brewster, "are scarcely surpassed by the fire of the diamond."

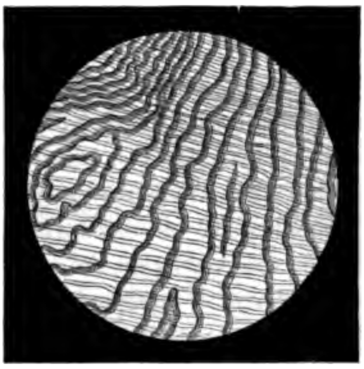

FIG. 248.- Striæ of mother-of-pearl seen with a magnifying power of 20,000 diameters.

The following is another phenomenon which seems to belong to the phenomena of interference, as it is explained by M. Babinet; and the description of which we take from the account given by the observer, M. A. Necker:—

"To enjoy the sight of this phenomenon," he says, "the observer should stand at the foot of a hill, interposed between himself and the spot where the sun sets and rises. He is then completely in the shade; the upper edge of the hill or mountain is covered with woods, trees, or detached bushes, which appear black against a perfectly clear and bright sky, except at the place where the sun is on the point to appear or disappear. There the whole of the trees and bushes which crown the summit—branches, leaves, trunks, &c.—appear with a bright and pure white, and shine with a dazzling light although projected on a background, which is itself luminous and bright as the part of the sky near the sun always is. The smallest details of the leaves and little branches are preserved in all their delicacy; and it might be said that the trees and forests are made of the purest silver, with all the art of the most skilled workman. Swallows and other birds, which fly across this region, appear as sparks of dazzling whiteness."

To those who know how to observe, Nature has a magnificence which the skill of the most ingenious experimenter can never approach. That which makes the merit of the inquirer is not so much to reproduce her—to multiply the phenomena, the pictures of which she shows us—as by dint of patience, sagacity, and genius, to discover the reasons of things, and the laws of their manifestations. From this point of view, natural philosophy is one of the grandest studies which the human mind can pursue.

CHAPTER XIV.

COLOURS OF THIN PLATES.

The soap-bubble—Iridescent colours in thin plates—Newton's experiment on coloured rings; bright and dark rings—Laws of diameters and thicknesses—Coloured rings are phenomena of interference—Analysis of the colours of the soap-bubble.

THE most beautiful and brilliant phenomena are not always those which require the most costly and complicated instruments to produce them. Who among us, in his childhood, has not amused himself, with a pipe or straw and soap and water, in blowing and throwing into the air bubbles of the most perfect form and the most delicate and varied colours?

At first, when the sphere of the bubble is of small diameter, the pellicle is colourless and transparent. By degrees, the air which is blown into the interior, pressing equally on all parts of the concave surface, increases the diameter while it diminishes the thickness of the envelope; it is then that we see the appearance, at first feeble and then brighter, of a series of colours arising one after the other, and forming by their mixture a multitude of iridescent tints, until the bubble, diminished in thickness, can no longer offer sufficient resistance to the pressure of the gas which it encloses. Black spots then present themselves at the top, and soon the bubble bursts. It is this last part of the phenomenon which is represented in Plate VII.; and, at the upper portion of the liquid sphere, the black spots which announce its disappearance may be observed.

This simple experiment and childish recreation, which offers so much attraction to the eye of the lover of colours, is not less beautiful or interesting to the man of science. Newton made it the object of his studies and meditations, and, since the time of this great man, the colours of the soap-bubble hold a legitimate place among the most curious of optical phenomena. Moreover, this is one particular instance of a whole series of phenomena, observed whenever light is successively reflected and refracted by surfaces which bound thin plates of transparent bodies. Solids, liquids, and gases are equally suitable for this kind of experiment. Crystals which can be reduced to very fine laminæ by cleavage, like mica, gypsum, talc, glass blown into extremely thin bulbs, the surface of annealed steel which retains a thin coating of oxide, show iridescent colours similar to those of a soap-bubble. The bright shades which ornament the membranous wings of dragon-flies, those seen on pieces of glass after exposure to damp, and on the surface of oily water, belong to the same series of phenomena. They are studied in physics under the common denomination of *the colours of thin plates.*

Before speaking of the cause of this decomposition of light into its constituent colours, we will endeavour to give an idea of the conditions under which it is produced, and the laws which govern the succession of tints, at first sight so changeable and mobile. Let us follow Newton in his celebrated experiments.

The starting-point of this great physicist was the following observation. He says, in his "Optics," that "having pressed two prisms strongly together, so that their sides touched each other (which were perhaps very slightly convex), I perceived that the place where they were in contact became quite transparent, as if there had been here only a single piece of glass. For, when the light fell on the air comprised between the two prisms so obliquely that it was totally reflected, it appeared that at the place of contact it was entirely transmitted. Looking at this point, a black and obscure spot was seen, like a hole, through which objects placed beyond it would distinctly appear."

Newton, having turned the prisms round their common axis, saw the gradual appearance around the transparent spot of a series of rings alternately bright and obscure, and coloured with different tints. To account better for the production of these rings, he used two glasses, one plano-convex, the other convex on both sides; and both of great radius of curvature. He then placed one over the other, and pressed the convex side gently on the plane side; in this position the two glasses had between them, around the central point of contact, a layer of air,—a very thin meniscus, the thickness of which, at the centre *nil*, continued to increase imperceptibly. The following are the phenomena which he observed:—

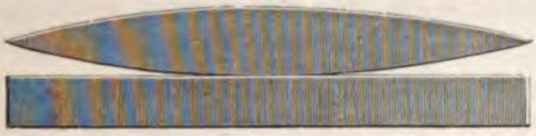

FIG. 249.—Thin plate of air comprised between two glasses, one plane, the other convex. (Newton's experiment of coloured rings.)

Receiving the reflected light in a direction nearly normal to the plane surface of the layer of air, he saw around the central point of contact a series of differently coloured concentric rings, becoming narrower as they were further from the centre. Each

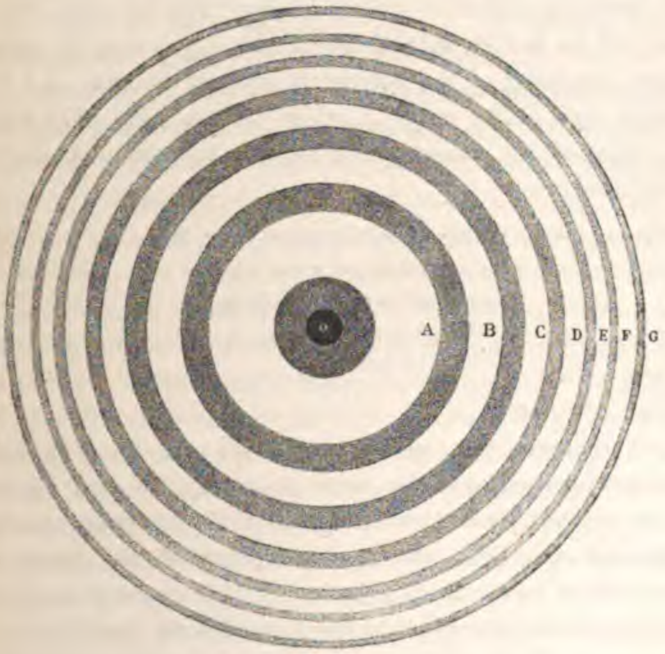

FIG. 250.—Newton's coloured rings.

colour appeared, at first, as a circle of uniform tint, which circle expanded as the pressure on the upper glass was increased, until a new colour issuing from the centre transformed it into a coloured ring. Lastly, at the centre itself, there appeared a black spot.

The following is the order and colour of the rings represented in Fig. 250. The colours indicated start from the centre O:—

From O to A,	black, blue, white, yellow, red ;
" A " B,	violet, blue, green, yellow, red ;
" B " C,	purple, blue, green, yellow, red ;
" C " D,	green, red ;
" D " E,	greenish blue, red ;
" E " F,	greenish blue, pale red ;
" F " G,	greenish blue, reddish white.

If, instead of receiving the light reflected on the two surfaces of the thin plate, we look at ordinary light through a system of two similar lenses, a series of coloured rings will be seen, but their colours will be feebler than those of the rings seen by reflection. Moreover, the order of the colours is entirely different, and, instead of a black spot at the centre, a white spot is seen. The following is the series of the various tints forming the coloured rings seen by transmission:—

White, red-yellow, black, violet, blue ;
White, yellow-red, violet, blue ;
Green, yellow-red, green-blue, red ;
Bluish green ;
Red, bluish green ;
Red.

If we compare this second series with the first, we see that the tints which occupy the same order in the two systems of rings are precisely complementary, so that the transmitted light and the reflected light at any one point of the layer of air produce white light when re-united. This consequence of the two experiments has been verified by Young and Arago, who, having placed the two glasses in such a manner as to cause both the reflected and transmitted lights to reach the eye with the same intensity, saw the rings disappear.

In order to observe the rings, Newton used the various simple colours of the spectrum. In this instance he perceived, by reflection, rings which were alternately black and bright,—the latter presenting the tint of the simple colour used. But the diameters of the rings varied in size, according to the colour of the light, and they widened on passing from the violet to the red. We can therefore understand how it is that the rings obtained with white light are iridescent. The different colours of which white light is formed, produce each its series of rings; but as the dimensions are different, the superposition is not exact; the dark rings disappear because they are again covered by other shades of light, except at the centre, and only when these shades are blended together in a proper proportion does the one ring of white light before observed appear. In introducing water between the glasses, the rings are still visible, but they are smaller and narrower, and the tints are fainter. Lastly, if, instead of a gaseous or liquid medium, the space between the two glasses is a vacuum, coloured rings are still seen, showing no perceptible difference from those given by air.

Newton, with his accustomed sagacity and precision, could not confine himself to the proving of these facts and others the details of which we cannot enter into; he sought out the law of the production of the rings, and thus he succeeded in tracing to the same principle the different phenomena described at the commencement of this chapter,—the iridescent colours of soap-bubbles and thin plates in all solid, liquid, and gaseous substances. He carefully measured the diameters of the successive rings obtained with monochromatic light, at the moment when the black spot of the centre indicated that the surfaces were in contact. From it he deduced the geometrical ratios, which give the relation of the diameters to the thicknesses of the thin plate, and these thicknesses themselves; and he determined the following laws:—

The squares of the diameters of the bright rings, seen by reflection, are related in the ratio of the odd numbers, 1, 3, 5, 7, 9.

The squares of the diameters of the dark rings are as the even numbers, 2, 4, 6, 8.

In regard to the rings seen by transmission, as they occupy precisely inverse positions, each obscure ring being replaced by a bright ring, and each of those by a dark ring, their diameters evidently follow the same laws, and the series of numbers is inverted.

So much for the relative dimensions of the bright and dark rings. As to the thicknesses of the layer of air interposed between the glasses, they continue to increase from the centre towards the extremities; but, if the values which correspond to the rings of the different orders are sought for, we find that these values are odd numbers for luminous rings, and even numbers for black or obscure rings.

These laws, although so simple, are general. Newton concluded that the phenomenon of coloured rings depends on the variable thickness of the thin plate interposed between the two surfaces, and the nature of the substance of which it is composed, but not at all on that of the glasses between which it is interposed. He endeavoured to connect it with the emission theory of light, supposing that the luminous rays, on being propagated, undergo periodical changes which sometimes render them apt to be reflected and sometimes apt to be transmitted! In the present day, as the undulatory theory is admitted, the coloured rings are explained in a more simple manner on the principle of interference. A ray of light which penetrates to the first surface of the plate is partly reflected and partly transmitted; transmitted as far as the second surface, where it is again reflected. The two rays, thus reflected on each surface, interfere, as we have already seen, and are destroyed or augmented according as the delay of the second equals an odd number of half-lengths of wave, or an even number of these same lengths. Hence, darkness in the first case, and light in the second, or, in other words, dark rings and bright rings.

Analysis applied to this interesting case of the undulatory theory also proves the laws of the diameters and thicknesses, which Newton first discovered by experiment. As the lengths of the waves vary according to the nature of the simple light, and diminish in passing from red to violet, we see that the rings of this latter colour must become narrower than the red rings. Now, in what way is this theory applicable to the phenomenon of the soap-bubble colours, colours so variable and changing, and which are continually mixed and blended with each other?

Newton showed the identity of the coloured rings obtained by means of glasses, and those which appear on bubbles. To study these, he took the precaution of protecting the blown soap-bubble from the influence of the external air, which, causing the thickness to vary irregularly, changes the colours one into the other, and thus prevents them from being exactly observed. He says, "As soon as I had blown one, I covered it with a very transparent glass; and by this means its different colours appeared in regular order, like so many concentric rings surrounding the top of the bubble." When these precautions are taken, the coloured rings visible at the top of the bubble are seen slowly spreading out, in proportion as the flow of the water towards the bottom of the liquid sphere renders this thinner, and, after having descended to the base, each disappears in its turn. Fig. 251 shows the disposition of these coloured bands.

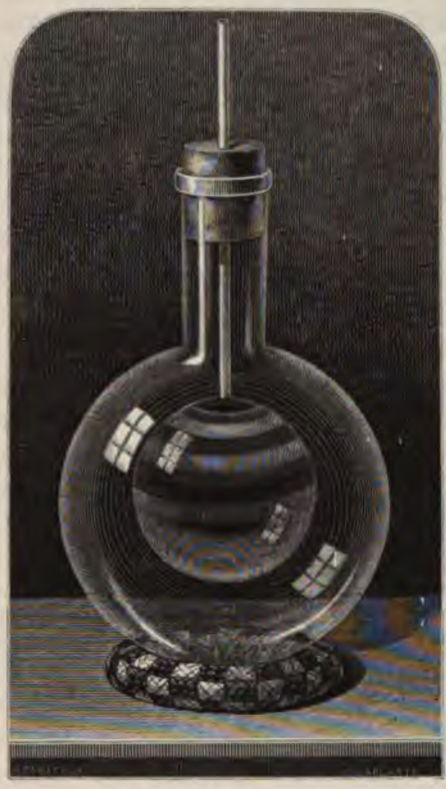

FIG. 251.—Colours of thin plates in the soap-bubble.

The phenomenon thus regulated loses its beauty from an artistic point of view, but in the scientific it gains in interest. In Plate VII. the zones of several rings can be seen, in spite of the irregularity of colour and their mixture. By degrees, the bubble becomes so thin at the top that the black spot makes its appearance, often mixed with smaller and darker spots; and almost immediately afterwards the bubble bursts and disappears.

According to Newton, the following is the exact order in which the coloured rings succeed each other from the first coloration of the bubble until its disappearance:—Red, blue; red, blue; red, blue; red, green; red, yellow, green, purple; red, yellow, green, blue, violet; red, yellow, white, blue, black.

Now, if we compare this series with that of the coloured rings obtained by means of the two glass surfaces in the first experiment, it will be noticed that they are arranged exactly in the opposite order, and this is as it should be, if the same cause produces both these effects. At the commencement, the bubble is too thick for the appearance of colours; it is colourless. Then its thickness diminishes more and more, so that at last the black corresponding to the least thickness appears exactly like the black spot of the first ring, which is found at the point where the two glass surfaces are in contact. This refers to colours seen by reflection. The bubble, once formed, ought to be observed in such a manner that it can reflect towards the eye the light of a whitish sky; and, in order to better distinguish the rings and colours, a black ground should be placed behind it. But the soap-bubble may also be observed by looking at ordinary light through it. Coloured rings are again formed; but they are of small brilliancy, and their successive colours are complementary to those given by reflected light. It is easy to assure oneself of this fact. If we examine the bubble by the light of clouds reflected to the eye, the colour of its circumference is red; at the same instant, another observer, looking at the clouds through the bubble, will find that its circumference is blue. On the other hand, if the contour of the bubble is blue by reflected light, it appears red by transmitted light.

Now it is easy to understand why the soap-bubble, observed in the open air, presents in the iridescent colours of its surface that irregularity, that mobility, that perpetual mixture of tints which causes it to be one of the most beautiful phenomena due to the decomposition of light by interference. The agitation of the air around the bubble, added to the want of homogeneity in the soapy water in different parts, and to the evaporation which takes place in a very unequal manner, produces numerous currents in the liquid pellicle, which, opposing the action of gravity in every direction, prevents the water from descending by regular zones towards the base of the bubble. Its thickness thus varies from one point to another, and, as it is on this thickness that the production of the different tints depends, these are distributed in the most varied manner. On the other hand, in a closed flask the air being saturated with vapour, evaporation and the agitation due to the external air no longer exist, and the rings appear with the regularity indicated by calculation.

We have forgotten to mention that the laws discovered by Newton regarding rings furnish a means of calculating the thickness of the liquid film of any given colour. At the point where the black spots are situated this thickness is the least; and it is then about the ten-thousandth part of a millimetre. Hence it follows that, if one could produce a soap-bubble uniformly of this thickness, it would be completely invisible.

CHAPTER XV.

DOUBLE REFRACTION OF LIGHT.

Discovery of double refraction by Bartholin—Double images in crystals of Iceland spar—Ordinary and extraordinary rays; principal section and optic axis—Positive and negative crystals—Bi-refractive crystals with two axes, or biaxial crystals.

ERASMUS BARTHOLIN, a learned Danish doctor, who lived at Copenhagen towards the middle of the seventeenth century, in examining some crystals which one of his friends had brought him from Iceland, was surprised to observe that objects appeared double when seen through them. He noticed this singular phenomenon in 1669, and described the circumstances of the case in a special memoir. Twenty years later, Huyghens undertook the study of what has since been called *double refraction;* he determined the laws, and propounded a theory in accordance with the principles of the undulatory theory, of which he had laid the foundations.

Since Bartholin's discovery and Huyghens' observations, these phenomena have been studied in all their phases, and the whole now constitutes an entire branch of optics. Before describing the principles of these phenomena, we will call to mind that which happens when a beam of light falls on the surface of a transparent medium like water or glass. On reaching the surface, part of the luminous beam is reflected regularly, in such a manner as to give an image of the object whence it emanates; another portion is reflected irregularly in all directions. For this reason the light returns on its path, or if we like, changes its path by changing its medium. The other portion of the ray of light penetrates into the transparent substance, when it is propagated without altering its direction, if the incidence is normal; whereas it is refracted, if the ray falls obliquely on the surface. But in both cases the ray remains simple; it is still simple, when it emerges from a transparent medium, so that the eye which receives it only sees a single image of the luminous source. This, however, is by no means always the case; certain substances act upon a ray of light in its passage through them and split it up into two, whence two images of the object, instead of one, are seen, as Bartholin first proved.

In lodes and metamorphic limestones and clays, a mineral is found which crystallizes in the form of a solid rhombohedron with six parallel sides, which is very transparent and colourless; its chemical composition shows it to be a carbonate of lime with traces of protoxide of manganese. The most beautiful specimens come from Iceland, and attain a thickness of several inches; the mineral is known under the name of *Iceland spar.*

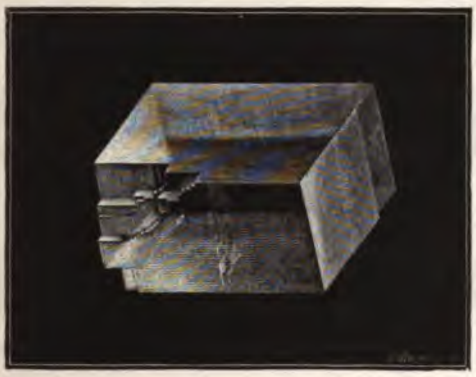

FIG. 252.—Specimen of Iceland spar.

Crystals of this kind are split with the greatest ease in certain directions, so that an exact geometrical form can be given them, which is more convenient for the study of their optical properties. The rhombohedron is then bounded by six lozenges equal among themselves.

Each of these lozenges has two obtuse angles, measuring 101° 55′, and two acute angles of 78° 5′. Of the eight solid angles which form the summits of the crystal, six are formed of an obtuse angle and two acute angles; the two others, of three obtuse angles.

Let us imagine that these two latter are joined by a straight line: this diagonal of the rhombohedron is of great importance in reference to the phenomena of which we are about to speak; this is called—we shall presently see why—the *optic axis* of the crystal.

We will now describe the phenomena of double refraction, which can be easily observed by means of a specimen of Iceland spar.

Let us take a piece of this crystal; place it on a line of writing, and look through it: we witness the phenomenon which struck Bartholin. Each letter is doubled. Let us, also, notice that each separate image is not so black as the letter itself: it has a greyish tint, and that this has nothing to do with the absorption of light by the crystal is evident, because the tint is black where the two images are superposed. The edges of the crystal itself seen by refraction appear double; and a straight line traced on paper is changed into two parallel lines. If we allow a beam of solar light to fall on one of its sides, the luminous ray issues as a double ray and forms two separate images on a screen, the distance between them depending on the inclination of the incident ray to the side of the crystal. We will now go farther into the analysis of the phenomenon; and to simplify the experiment, let us examine one part at a time. Seen through the crystal, the images appear double; but if we turn the crystal on itself, parallel to the faces of incidence and emergence, we observe that one of the images turns round the other, and when an entire revolution has been described by the crystal, one image returns to its first position, after having described a circle round the other immoveable one. When, instead of observing one point, the same experiment is made on a straight line, it will be noticed that in two different positions of the crystal one of the lines, which appears to be moved parallel to the other, attains a maximum digression; in two other positions, the two images seem to coincide. But this coincidence is only apparent; for if a point on the observed line

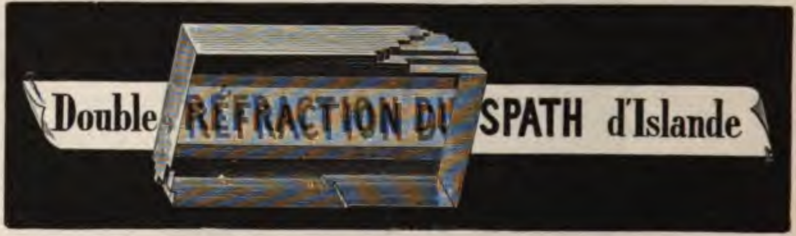
Double RÉFRACTION DU SPATH d'Islande

FIG. 253. – Double images of objects seen through a crystal of Iceland spar.

is marked, we see the double image of this point, where the images of the lines are superposed. Then the rotation of one of the images round the other takes place in this case, as in the preceding one. Let us now see why the name of *ordinary image* is given to the immoveable image, and that of *extraordinary image* to that which rotates round the first. The reason is, that the refracted ray which produces the immoveable image follows during its path the laws of simple refraction, such as were enunciated by Snellius and Descartes, whilst the other ray does not obey the same laws.[1] This characteristic difference between the two images can be exhibited in many ways. If we cause a ray of light to fall perpendicularly on one of the faces of the crystal, it will be bifurcated in penetrating into the interior; but one of the rays will follow the direction of the incident ray, and will not be refracted on its emergence: this is the ordinary ray, which obeys Descartes' law. The other ray will be deviated from the direction of the incident ray, both on its entrance into and emergence from the crystal: this is the ray which produces the extraordinary image.

When the incidence is oblique, the two rays are refracted; but the ordinary ray is equally deviated whatever the position of the crystal may be, provided that the sides of incidence and emergence remain parallel to their first position; in a word, its path is that which it would preserve through a piece of glass with parallel sides. It is not so with the other ray, which gives rise to the extraordinary image, since this image, as we have already shown, turns round the first, if the crystal be caused to revolve parallel to itself.

In this movement of the extraordinary image there is a circumstance which must be noted. If the crystal be placed on a sheet of paper on which a point is marked, and the eye be in the plane of incidence, the ordinary refracted ray will be also in this plane, as the law of simple refraction shows, and the ordinary image O of the point will be on the line I I of the plane of incidence with the paper (Fig. 254). But it will not be the same with the extraordinary image E, and the lines which join the two images O E will make an angle with the line of which we have spoken. Now, we observe that this line O E always remains parallel, during the rotation movement, to the bisector A D of the obtuse angle of the side parallel to the plane of the paper. Also when, owing to this movement, this bisector is placed parallel to I I, the extraordinary image is itself on this line, and the two refracted rays are both in the plane of incidence.

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[1] In a word, on the one hand, the extraordinary refracted ray is not generally in the plane of incidence; and, on the other, the relations of the sines of the angles of incidence and refraction do not remain constant.

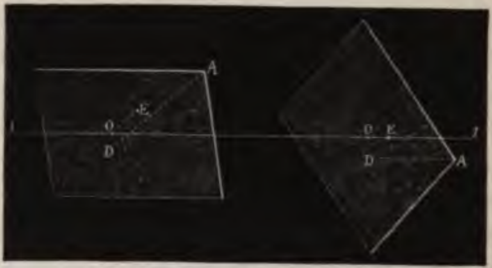


FIG. 254.—Positions of the extraordinary image in relation to the plane of incidence. Principal section.

There is then, among the sections which cut the crystal perpendicularly to one of its sides, a section of such a nature that if the incident ray were found contained there, the extraordinary ray would obey the first law of simple refraction exactly like the other ray. This plane is called the *principal section*. Each plane, perpendicular to one of the faces of Iceland spar, and parallel to the small diagonal of the lozenge, or to the bisector of the obtuse angle, is one principal section of this face.

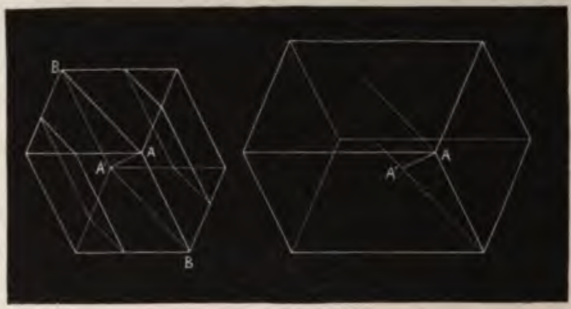


FIG. 255.—Principal sections and optic axis of Iceland spar.

Each principal section is parallel to the optic axis, and this condition suffices; so that if an artificial face were cut in the crystal, any plane perpendicular to this face and parallel to the optic axis, would also be a principal section of the artificial face. Lastly, if we make an artificial face A B C perpendicular to the optic axis N I, every ray which falls on this face will necessarily be in a principal section, and the two refracted rays will always be in the plane of incidence. In this case observation proves that if the incident ray is normal to the artificial face, the refracted ray alone remains. This is therefore a direction in which the phenomenon of bifurcation vanishes: double refraction no longer takes place, when the incident ray is parallel to the optic axis.

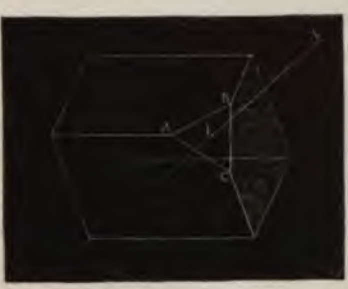


FIG. 256.—Artificial section perpendicular to the optic axis.

Monge made a remarkable experiment, very easy to repeat, which shows us the path followed by the rays emanating from a luminous point through the crystal in giving rise to the two images, ordinary and extraordinary, of the point. If we examine the double image of a point S (Fig. 257), situated at some distance from the lower face, and place underneath this face an opaque card, *a b*, we shall notice with surprise that the most distant image of the card first disappears; and this is explained as follows. A luminous

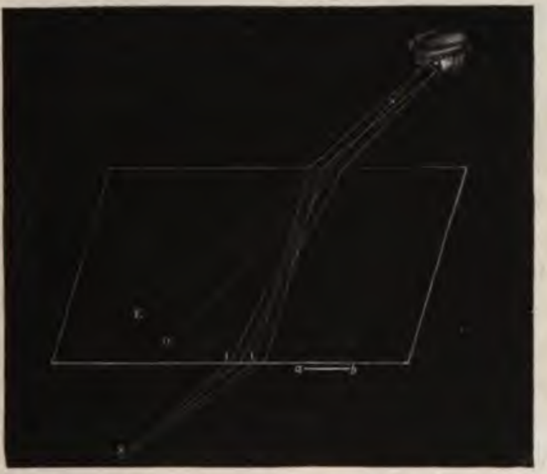


FIG. 257.—Crossing of the rays which produce the ordinary and extraordinary image.

incident pencil, S I, is bifurcated, and gives two refracted rays; whence on issuing from the parallel face, two emergent rays arise; they diverge, and one of them can then only penetrate the eye: let us suppose this the one which produces the ordinary image O. An incident pencil, near the first, will also give two emergent rays, one of which will penetrate to the eye and will produce the extraordinary image E. As the faces of the crystal are parallel, each emerging ray is composed of rays parallel to those of the incident ray. As those which produce the image are concentrated in the eye, it is necessary that the corresponding refracted rays cross each other in the crystal.

Monge's experiment is explained thus: the card *a b* first intercepts the pencil which produces the most distant image, and it is this—the extraordinary image E—which must naturally disappear first.

Such are the most remarkable circumstances which constitute the phenomenon of double refraction. The laws which govern this phenomenon are too complex to allow us to explain them in an elementary work like this. But we will endeavour to give, in a few lines, some idea of the difference which exists between simple and double refraction.

We have already said that the ordinary ray follows the two laws of Descartes; in other words, that the refracted ray is always in the plane of incidence, and that if the angle of incidence is changed, the relation which exists between its sines and those of the refracting angle is always constant. The extraordinary ray only follows the first of these laws, if the incident ray is in a principal plane. But it does not follow the second, so that the relation of the sines, which is called the index of refraction, varies according to the angle that the incident ray makes with the optical axis of the crystal. Is this angle *nil*, or is the incident ray parallel to the optical axis? In this case only, double refraction disappears; one of the images is blended with the other: there is equality between the ordinary and extraordinary indices of refraction.

As the angle increases, so does the inequality of these indices, and it is a maximum if the incident ray is perpendicular to the optic axis. For Iceland spar, the only crystal endowed with the power of double refraction that we have hitherto examined, the index of refraction of the ordinary ray is greater than that of the extraordinary ray. The contrary takes place, if certain other bi-refractive substances are employed, such as rock-crystal. In order to explain the cause of this difference we should be obliged to expound the entire theory of simple and double refraction, according to the undulatory theory, to show that refraction is caused by the difference of velocity which the ether waves undergo in passing from one medium into a more refractive one; that the ordinary ray acts as if it were in a homogeneous, non-crystallized medium, whilst the extraordinary ray is propagated with more or less facility, according as it is moved in such or such direction relatively to the position of the crystalline molecules.

In Iceland spar, the velocity of the extraordinary ray is the greatest; and the reverse is the case in rock-crystal. Hence the names of *positive* and *negative* crystals have been given to substances which possess double refraction according as they are included in one or the other category, the type being for the first, rock-crystal, and for the second, Iceland spar. Tourmaline, rubies, emeralds are negative crystals; quartz—the mineralogical name of rock-crystal—sulphate of potassium and of iron, hyposulphate of lime, and ice are numbered with the positive crystals. Double refraction is also produced in a certain class of crystalline substances known under the name of crystals with two axes, or biaxial crystals. Topaz, arragonite, sulphate of lime, talc, feldspar, pearl, and sugar are crystals with two axes: in each crystal of this kind there are two different directions in which the incident ray passes without being bifurcated; these two directions are the *optic axes* of the crystal. But there is an essential difference between the phenomena of double refraction in crystals with one axis, or uniaxial crystals, and those of crystals with two axes, or biaxial crystals. In the first, one of the two refracted rays follows the laws of simple refraction; in the others, the two rays are both extraordinary: neither of them follows Descartes' laws. Fresnel's experiment proves the fact very simply. A topaz is divided into several pieces cut

FIG. 258.—Rock crystal.

in different directions, and these pieces are fastened together by their plane surfaces so that the form of a parallelopiped is given to the whole. Then on looking at a straight line, two images of the line are seen, and each of these images is a broken line of which the different portions correspond to the fragments of the topaz: now, if one of the systems of refracted rays followed Descartes' law, the image produced would be a straight line, for the direction of the rays in the prism would then be independent of the direction of the optic axis in each piece which composes it. Experiment thus proves that the two rays are both extraordinary rays. We shall soon find another means of distinguishing crystals with one or two axes from each other.

We may conveniently end this chapter by enumerating the refractive media in which phenomena of this order are not manifested, or, in other words, which are endowed with simple refraction. First there are gases, vapours, and liquids; then, among substances which have passed from a liquid to a solid state, those whose molecules have not taken a regular crystalline form, such as glass, glue, gum, and resins; lastly, crystals whose primitive form is the cube, regular octahedron, and the rhomboidal dodecahedron. It must be added that the bodies belonging to these two last categories can acquire the property of double refraction when they are subjected to violent compression or expansion; also when their different parts are unequally heated. Certain solids belonging to the vegetable or animal kingdom,—horn, feather, and mother-of-pearl,—are also endowed with double refraction.

CHAPTER XVI.

POLARIZATION OF LIGHT.

Equal intensity of the ordinary and extraordinary images in a doubly refractive crystal—Natural light—Huyghens' experiments; variations of intensity with four images; polarized light—Polarization of the ordinary ray; polarization of the extraordinary ray: the two planes in which these polarizations take place—Polarization by reflection.

WHEN a luminous object is viewed through a double refracting crystal, a rhombohedron of Iceland spar for instance, we know that two distinct images are seen; one ordinary, following the law of simple refraction, the other extraordinary, the properties of which we have indicated in the preceding chapter. The latter is easily recognized as it revolves round the other, when the crystal is made to rotate in a plane parallel to the faces of incidence and emergence of the rays. It is now necessary to remark that, in all these positions, the relative intensity of the two images has not varied: the brightness of each of them is the half of that of the luminous object, as can be easily proved by direct observation. Let us suppose that we examine a small white circle on a black ground. In all parts where they are separated, the two images, ordinary and extraordinary, of the circle present a greyish tint of the same intensity, and the brightness equals that of the object when the two images are superposed. Indeed, the same phenomenon always takes place, whatever the respective colours of the object and ground may be. The same result is also shown if we allow a ray of solar light to fall on the crystal and receive the two refracted rays on a converging lens, the two images being projected on a screen (Fig. 259). If the crystal is made to revolve parallel to the face of incidence, the two images are displaced, each describing a circumference of a circle, and we observe that in every position the luminous intensities are equal. If the two images are partly superposed, the brightness of the superposed parts will be double that possessed by the separate parts, as shown in Fig. 260.

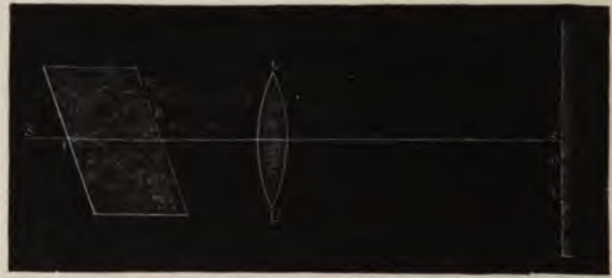


FIG. 259.—Propagation of ordinary and extraordinary images of a doubly refracting crystal. Equal intensity.

An old and beautiful experiment, due to Huyghens, proves that the rays which emerge from Iceland spar have acquired new and remarkable properties, after their deviation in the crystalline medium, —properties which they did not possess before passing through the crystal. This experiment consists in receiving the ordinary and extraordinary rays, after their emergence from the first rhombohedron, on a second crystal, and examining the relative intensities of the images which they produce, when the second crystal is caused to revolve over the first. The following is a very simple method of observing the phenomena which are thus produced; it is that which Huyghens himself devised. Let us place the first crystal on a black spot on a white ground; there will be two images of equal intensity. We will now place a second piece of Iceland spar on the first, and it must be placed so that their principal sections coincide; in order that this condition may be realized, the faces of one must be placed parallel to the faces of the other: there will be only two images of the

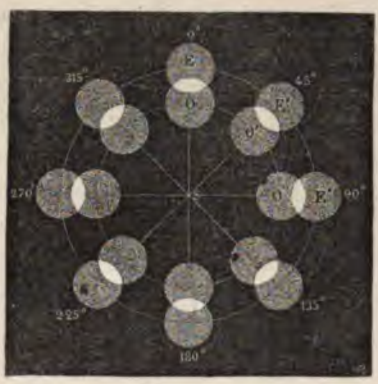


FIG. 260.—Equal intensity of ordinary and extraordinary images.

same intensity as before. Only, the two images, ordinary and extraordinary, will be more separated than by one crystal. The same effect would take place if the principal sections of the two rhombohedra remained in the same plane, or in parallel planes when even the two opposite faces of the crystals were not parallel; and it is not necessary that, in the first position, the two rhombohedra touch each other.

We observe then, already, a difference between the luminous ray before its refraction by Iceland spar, and each emerging ordinary or extraordinary ray; whilst the first is bifurcated in penetrating the crystal, it appears that the two others remain simple in penetrating a second crystal.

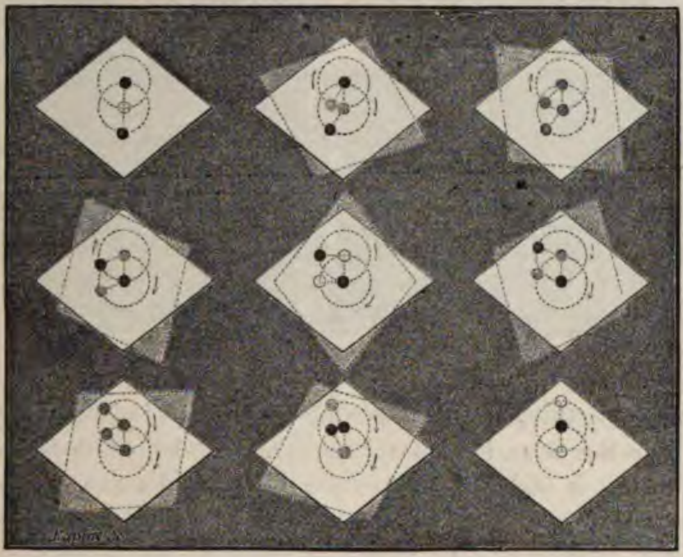


FIG. 261.—Huyghens' experiment. Variations in intensity of the images seen when one prism of Iceland spar is rotated over another.

Let us now slowly turn the upper crystal, so that the principal section makes greater and greater angles with that of the first. We then see four images appear; each of the two first will be divided, but the equal intensity which characterized them is not retained in the others. Of these four images, arranged at the angles of a lozenge with regular sides, but with unequal angles, two proceed from double refraction, in the upper crystal, of the ordinary emergent ray; the two others proceed from the double refraction of the extraordinary ray. But an important difference to be indicated is that, in general, each couple is characterized by a difference in the luminous intensity of the images. Fig. 261 represents their relative positions and intensities for angles comprised between 0° and 180° of the principal sections of the two crystals. If the principal sections are at right angles, only two images are seen: if they make an angle of 180° and the crystals have the same thickness, the two images are superposed; in the latter case, the deviations made by each crystal being in opposite directions, there is only one image.

It already follows from this first experiment that each ray of light which has passed through a doubly refracting crystal no longer possesses, after its passage, the same properties in all directions; for in certain directions it is no longer susceptible of undergoing a new bifurcation, and in others, the two rays into which it is divided have no longer the same luminous intensity. To distinguish these new properties, it is said that light which has passed through a doubly refracting crystal is *polarized light.*

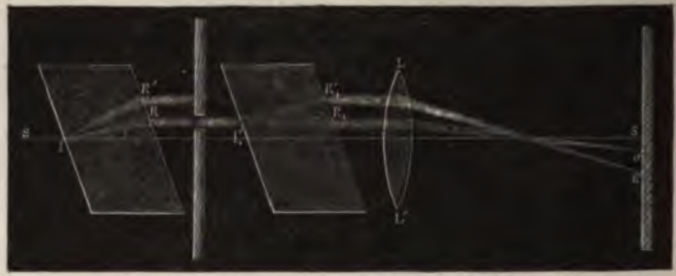


FIG. 262.—Polarization of the ordinary ray by double refraction.

But it is important to point out precisely the phenomena just described. Let us suppose that a ray of solar light, S I (Fig. 262), is allowed to fall on the first crystal of Iceland spar, its principal section being vertical. This ray is divided in the plane of the section into two rays: the one ordinary, I R; the other extraordinary, I R'. If we intercept one of the two by a screen, and allow the other to pass through a second piece of Iceland spar, the luminous ray, on traversing the second crystal, will undergo double refraction: it will be divided into two rays,—I R, which is the ordinary ray, and I'R', which is the extraordinary one. Lastly, by the help of a lens, we will project the emerging rays on a screen, and examine what will happen if the second crystal is turned so as to produce at its principal section every possible angle with that of the first, from 0° to 360°. Fig. 263 shows the relative intensities of the two images if the ordinary ray from the first crystal has traversed the second; Fig. 264 shows on the contrary what these intensities are, when the extraordinary ray emergent from the first is allowed to pass through the second prism.

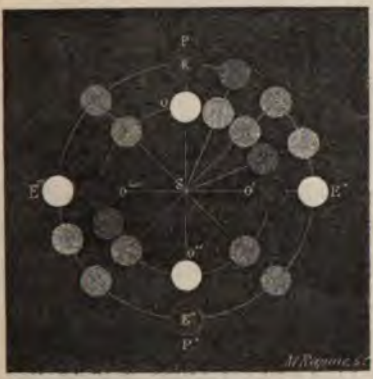


FIG. 263.—Division of the ordinary ray. Variable intensities of the images of the polarized rays.

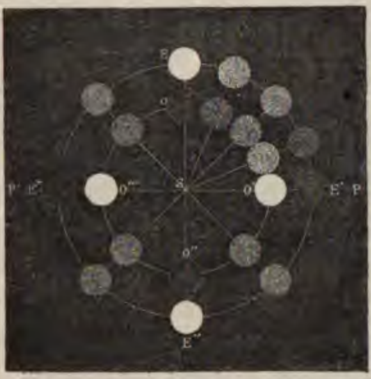


FIG. 264.—Division of the extraordinary ray. Intensities of the images of the polarized rays.

We may now sum up. A ray of ordinary light has entered the first crystal when it undergoes double refraction, and each of the rays which emerge has particular properties which are distinguished by saying that it is polarized: for this reason, the first crystal receives the name of polarizer. The second crystal is used to analyse the properties which each pencil has acquired by polarization: this is called the analyser.

The ordinary ray, on passing through the analyser, is divided into two rays, the intensity of which varies according to the angle the principal section of the second crystal makes with that of the first, and which gives two images, one ordinary, the other extraordinary. If this angle is 0° or 180°, the ordinary image alone exists with maximum intensity, the extraordinary image having disappeared; at 90° or 270° the extraordinary image has attained its maximum brightness, the other having disappeared. For intermediate positions where the second principal section forms angles of 45° with the first, the two images have the same intensity. Lastly, in other relative positions of the principal sections of the crystals, there is unequal intensity in one or other of the images. It is then said that the ordinary ray is polarized in the plane of the principal section; this plane is called the *plane of polarization*. Now, like the second ray, the extraordinary ray undergoes the same modifications on passing through the *analyser*, with the essential difference that as there is always a difference of 90° in the relative position of the principal sections, it is said to be polarized in a plane perpendicular to the first plane of polarization. Its plane of polarization makes a right angle with the principal section of the *polarizer*. Therefore the two rays, ordinary and extraordinary, proceeding from a ray of light which has undergone double refraction, are polarized at right angles.

Polarization by double refraction, such as we have just studied in Iceland spar, is produced in the same manner with all doubly refracting crystals. But it is not always easy to observe it on account of the slight separation of the ordinary and extraordinary rays. With Iceland spar itself it is necessary to have crystals of a certain thickness, in order that one of the rays can be more readily intercepted with a screen. To obtain this separation of the polarized pencils some very useful apparatus have been invented, among which may be mentioned Nicol's prism.

Nicol's prism consists of a long crystal of Iceland spar which has been cut in two in a plane perpendicular to the principal section. The two pieces again placed in their original positions are joined together by means of a layer of Canada balsam. The refractive index of this substance is intermediate between the refractive indices of the spar which correspond, one to the ordinary, the other to the extraordinary ray. Hence it follows, as has been accurately shown and confirmed by experiment, that if a ray of light enters in the direction of the length of the crystal and there divides into two by double refraction, the ordinary ray undergoes total reflection at the surface of the Canada balsam, whilst the extraordinary ray alone passes into the second half of the crystal and emerges from the opposite face.

Let us suppose that two of Nicol's prisms are used to work out Huyghens' experiment. It is evident that only two images will be obtained, those which proceed from the emergent ray; that is to say, from the extraordinary ray polarized by the first prism. If the principal sections of the two prisms are parallel, one of the images, the ordinary, is *nil*, the extraordinary one at its maximum brightness; if the principal sections are at right angles, both of them disappear, as the ordinary image which ought to have a maximum intensity undergoes total reflection, and the intensity of the extraordinary image is *nil*. The first prism, that which receives the ray of ordinary light, is the Nicol polarizer; the other is the Nicol analyser.

This property of Nicol's prism, of allowing only the extraordinary ray to emerge, belongs also to a natural crystal, tourmaline, which, when it possesses a certain thickness, strongly absorbs the ordinary ray. M. Biot discovered this remarkable property in 1815: it will enable us to quote from Sir J. Herschel another example of the polarization of light by double refraction.

FIG. 265.—Specimen of Siberian tourmaline.

"When we take one of these crystals, and slit it (by the aid of a lapidary's wheel) into plates parallel to the axis of the prism, of moderate and uniform thickness (about $\frac{1}{20}$th of an inch), which must be well polished, luminous objects may be seen through them, as through plates of coloured glass. Let one of these plates be interposed perpendicularly between the eye and a candle, the latter will be seen with equal distinctness in every position of the axis of the plate with respect to the horizon (by the axis of the plate is meant any line in it parallel to the axes of its molecules, or to the axis of the prism from which it was cut). And if the plate be turned round in its own plane, no change will be perceived in the image of the candle. Now holding this first plate in a fixed position (with its axis vertical, for instance), let a second be interposed between it and the eye, and turned round slowly in its own plane, and a very remarkable phenomenon will be seen. The candle will appear and disappear alternately at every quarter of a revolution of the plate, passing through all gradations of brightness, from a maximum down to a total or almost total disappearance, then increasing again by the same degrees as it diminished before. If now we attend to the position of the second plate with respect to the first, we shall find that the maximum of illumination takes place when the axis of the second plate is parallel to that of the first, so that the two plates have either the same positions with respect to each other that they had in the original crystal, or positions differing by 180°, while the minima, or disappearances of the image, take place exactly 90° from this parallelism, or when the axes of the two plates are exactly crossed. In tourmalines of a good colour, the stoppage of the light in this situation is total, and the combined plate (though composed of elements separately very transparent and of the same colour) is perfectly opaque."

Thus the beam of ordinary light which has passed through the first plate of tourmaline is polarized like that which emerges from a crystal of Iceland spar. All its sides, all its faces, if we may so express it, do not possess the same property. We shall now see that double refraction is not the only means of transforming ordinary into polarized light.

In 1808, Malus, a French physicist, famous for his beautiful researches on optics, while accidentally looking through a crystal of Iceland spar at the setting sun reflected by the window panes of the Luxembourg Palace, remarked with surprise that, on turning the prism, the two images changed in intensity; the most refracted was alternately brighter or less bright than the other, at each quarter of a revolution. On minutely analysing this phenomenon, he discovered that reflection at certain angles is sufficient to induce in a luminous ray the same properties which a ray possesses after having traversed a doubly refracting crystal such as Iceland spar. Huyghens' experiment, concerning which both Huyghens and Newton had in vain tried to produce a theory, was no longer an isolated phenomenon; and it was in the endeavour to explain it by Newton's theory that Malus was led to give the term *polarization of light* to the modification undergone by the luminous rays in the experiment just mentioned. Three years later, in 1811, Malus, Biot, and Brewster discovered separately polarization by simple refraction: Arago, chromatic polarization; and since then many new facts belonging to the singular modifications of the luminous rays in the phenomena just described have helped to form one of the most interesting branches of science, as fruitful of theory as of practical application. As the limits and elementary nature of this work do not allow us to enter into long details, we can only describe some of the more remarkable of these phenomena.

And first of *polarization by reflection.* When a beam of ordinary light falls obliquely upon a non-metallic mirror, as black glass, marble, or obsidian, it acquires by reflection the same properties as if it had traversed a double refracting crystal: it is *polarized.*

If a plate of black glass is placed on a table in front of an open window, and the light of the clouds reflected by the plate obliquely at an inclination of about 35°, the brightness of the mirror appears uniform. If, without changing the position, the bright surface is observed through a plate of tourmaline split parallel to its optical axis, and if this plate is made to turn in its own plane, the following variations will be seen in the brightness of the image of the clouds formed on the plate of glass. If the axis of the tourmaline is in a vertical plane, the image disappears; the plate of glass seems covered with a kind of dark cloud: when the axis is, on the contrary, horizontal, that is to say, parallel to the plate of glass, the darkness completely vanishes: lastly, in the intermediate positions of the axis of the tourmaline the brightness of the image gradually increases from the first to the second position. If the analyser, instead of being a plate of tourmaline, is a Nicol's prism, the variations of brightness of the image will succeed each other in the same manner: the minimum will take place when the principal section of the prism is vertical, and the maximum, when this section is at right angles to its first position.

From these experiments we infer that a luminous beam falling with an inclination of 35° 25′ (or, in other words, with an incidence of 54° 35′) on a plate of black glass, is, after reflection, polarized in the plane of this reflection. This angle of 54° 35′ is what is named the angle of polarization of glass: it is that in which the reflected ray can be completely extinguished by the polariscope analyser. This is expressed by saying that it is completely polarized. When the angle of incidence has another value, the image of the beam is not completely extinguished; in fact, the reflected ray is only partially polarized.

The angle of polarization varies with the nature of the reflecting substances. Thus, it is 52° 45′ for water, 56° 3′ for obsidian, 58° 40′ for topaz, 68° 2′ for diamond. Brewster made a very curious experiment in order to prove the difference which we shall presently point out between the angles of polarization of two substances,—glass and water for example.

He placed a plate of glass so that it might receive and reflect a beam of light at an incidence of 54° 35′, which is, as we have just seen, the angle of polarization of glass. He then observed the reflected beam with an analyser, in such a manner that all light disappeared. Now, if at this moment any one breathed on the glass plate, the image again appeared. This phenomenon is due to the reflection from a bed of water, the angle of polarization of water not being the same as that of glass.

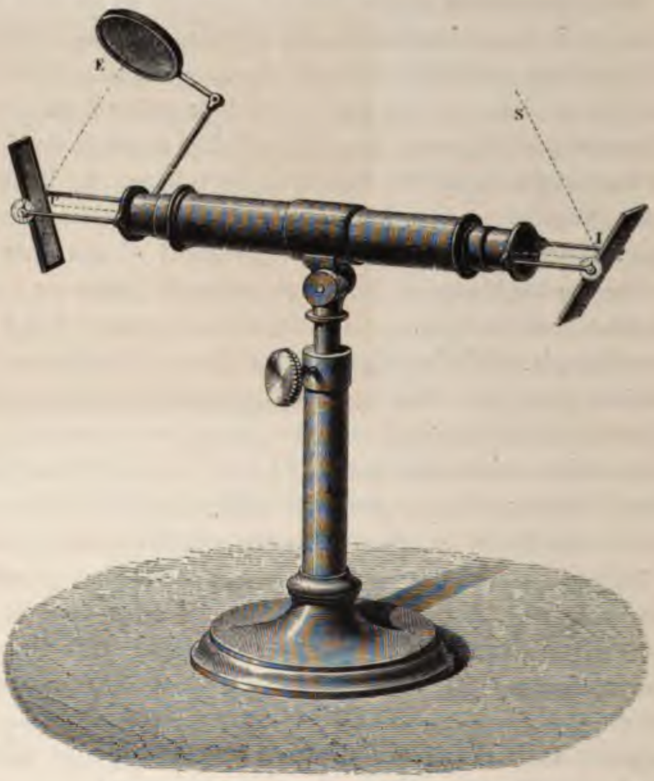


FIG. 266.—The polariscope of Malus perfected by M. Biot.

Malus invented an apparatus by the aid of which all the properties of polarized light by reflection can be studied. Besides those we have just described, there are others which characterize this light when it is reflected after falling on a second reflecting plate. Fig. 266 represents the apparatus of Malus modified and perfected by M. Biot. I is the polished plate for polarizing the ray of light S I by reflection from the surface of the plate; the reflected and polarized ray I I, then enters a tube blackened inside and furnished with diaphragms, and passes along its axis.

As it issues from the tube, the ray falls on a plate I′ of black glass, is again reflected, and either falls on the eye, or forms an image on a screen E. The frames which hold the two reflecting plates can be turned round on an axis perpendicular to that of the tube, so that their planes can make with the latter all possible angles; moreover, each plate can be turned in one of its positions also round the axis of the tube; so that for a given incidence of the luminous ray on the first plate, both the angle of incidence of the polarized ray on the other plate, and the angle of the second plane of reflection with the first, can be varied at will. By means of this apparatus it can be shown that the maximum brightness of the image takes place when the two planes of reflection coincide; and the minimum, when these two planes are at a right angle. Moreover, the ray is completely extinguished when the angle of incidence on each of the two mirrors is 35° 25′, provided always that the beam has not too great an intensity as in the case of solar light. Brewster discovered a very simple law which exists between the angle of polarization and the index of refraction of the substance which polarizes light by reflection, so that, if one of these elements is known, we can deduce the other. This law expresses the following geometric relation: the reflected ray I R, polarized at the angle of polarization, and the refracted ray I *r*, form a right angle. Simple refraction also polarizes light. This was discovered

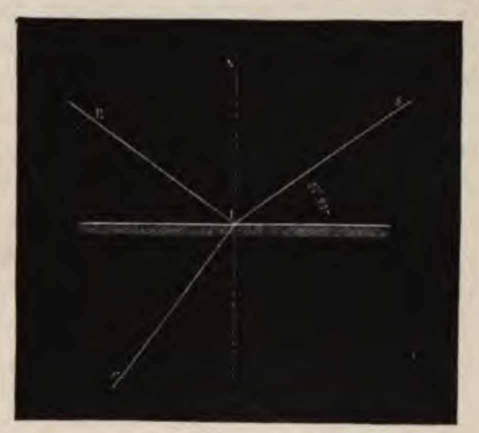


FIG. 267.—Relation between the polarized ray and the angle of polarization of a substance and the refracted ray. R′ I *r* is the right angle.

separately by Malus, Biot, and Brewster in 1811. The phenomenon can be proved by Biot's apparatus (Fig. 266) when the glass I has been replaced by a glass prism. If the prism is turned so that the ray issues perpendicularly to the face of emergence, it is found by turning the analyser I′, that the beam after reflection shows a maximum and minimum intensity, but not in a very decided manner. The light then is partially polarized: as the maximum of brightness takes place when the plane of incidence on the analyser is perpendicular to the place of incidence on the prism, we see that in this case the plane of polarization is perpendicular to the plane of refraction.

A completely polarized ray can be obtained by simple refraction if we cause it to successively traverse several parallel plates of glass at an angle of 35° 25′, which is, as we have seen, the angle of polarization of glass. These thin and polished plates must be laid one on the other, in such a way that a thin stratum of air is interposed between each plate: the apparatus thus arranged is called a glass pile; it is used as a polariscope by placing it in Biot's apparatus in place of the glass I′. We will not enlarge further on this curious class of phenomena, the detailed description of which would detain us too long, and which, besides, to be well understood, would require difficult theoretical developments. We only desire to initiate the reader into the fundamental facts the discovery of which has been the starting-point of this important branch of modern optics.

CHAPTER XVII.

CHROMATIC POLARIZATION.

Discovery of the colours of polarized light, by Arago Thin plates of doubly refractive substances; variations of colours according to the thickness of the plates—Colours shown by compressed and heated glass—Coloured rings in crystals with one or with two axes—Direction of luminous vibrations; they are perpendicular to the direction of propagation, or parallel to the surface of the waves.

"WHILE examining in a clear light a somewhat thin plate of mica by means of a prism of Iceland spar, I observed that the two images did not possess the same tint of colour; for one was greenish yellow, while the other was reddish purple, and the portion where the colours overlapped presented the ordinary colour of mica as seen by the naked eye. I noticed at the same time that a slight change in the inclination of the plate as regards the rays which traversed it caused a variation in the colour of the two images; and that if this inclination were allowed to remain constant and the prism in the same position, the plate of mica was caused to turn in its own plane. I found four positions at a right angle in which the two prismatic images were equally bright and perfectly white. If the plate of mica were left at rest while the prism was turned, each image was observed successively to acquire different colours, and to become white after each quarter of a revolution. In addition to which, for all positions of the prism and the plate, whatever might be the colour of one of the images, the other always presented the complementary tint; and wherever the two images were not separated by the double refraction of the crystal, the mixture of the two colours formed white."

It was in these terms that Arago, in a memoir read at the Académie des Sciences on the 11th of August, 1811, described the experiment which was the beginning of a series of discoveries, on the phenomena of coloration of polarized light. He instantly recognized that the light transmitted by a plate of mica was light polarized by reflection from the atmospheric strata: in dull weather, when the light from the clouds has the nature of common light, the two images seen through the plate of mica would show no trace of colour. Thus, in order to produce the phenomenon, the light which traverses the crystallized plate must have been previously polarized. This condition was placed beyond doubt by Arago, by means of several experiments in which he received, on a plate of mica, rays reflected by a mirror of black glass: he then noticed that the colours of the two images observed through Iceland spar were brighter when the light was reflected at an angle nearer to the angle of polarization of the glass. All doubly refracting substances cut in thin plates parallel to the axis, possess this same property of colouring the polarized light which traverses them; thus plates of gypsum (sulphate of lime) can be used, also rock crystal and Iceland spar. But the thicknesses of the plates which produce these colours vary in different substances, and in the case of each of them no coloured images can be obtained if the thickness is not comprised between certain limits. A plate of sulphate of lime must have more than 0mm. 425, and less than 1mm. 27, of thickness; a plate of mica less than 0mm. 085; a plate of rock crystal less than 0mm. 45. It is difficult to obtain colours with Iceland spar, because the thickness of the plate must not exceed the fortieth part of a millimetre. The inclination of the plate to the direction of the polarized rays influences the colours, which quickly change as this inclination varies. The thickness with the same inclination of the plate and the same position of the prism also influences the colours of the image; and M. Biot found that the laws of variation of these shades or tints are precisely those which Newton discovered for the coloured rings of thin plates obtained by the superposition of two lenses; but the thicknesses of the doubly refractive plates which correspond to the colours of Newton's various orders are much greater than those of the stratum of air enclosed between the lenses.

This property of the change of colour, according to the thickness, is employed to produce varied and curious effects. If, after having fastened a plate of gypsum on a piece of glass, a spherical cavity of large radius is hollowed out, and the plate is examined by means of Biot's apparatus, the light which reaches the eye, having been previously polarized before traversing the plate of gypsum and the analyser, a series of coloured concentric rays are seen, like those observed round the point of contact of the two lenses; if we engrave different objects in the hollow of the plate,—such as flowers, insects, and butterflies,—the depths of the engraving can be calculated at the different points, so as to reproduce the bright and varied colours of the natural objects. "Formerly we did better," said Mr. Bertin, recently, in a very interesting conference on polarization, "and profited by the circumstance to do honour to the author of these beautiful experiments. In the midst of a crown of leaves appeared the name of Arago, with the date of his discovery. From the contemporaries of the great man it was perhaps flattery; but now that he is no more, the suppression of this experiment in a course of physics is an act of ingratitude: we forget our dead to run after butterflies." It would be just to join to the name of Arago that of Brewster, who at the same time made nearly the same discoveries, and to whom we principally owe that of coloured rings in crystals with one or two axes. Before entering into details of these remarkable phenomena, we may state that glass, in the ordinary state, is not susceptible of showing the colours observed in crystallized plates, but it acquires this property by tempering, bending, and compression, and by the action of heat. Figures 268 and 269 show some of the appearances presented under these different circumstances by plates of glass of a certain thickness, and of either a rectangular or square form. The discovery of these phenomena is due to Seebeck (1813), and they are of the same nature as those just described. The following is a curious experiment of Biot related by M. Daguin in his "Traité de Physique:"—"Biot produced longitudinal vibrations in a band of glass about two metres in length, placed between the polarizer and

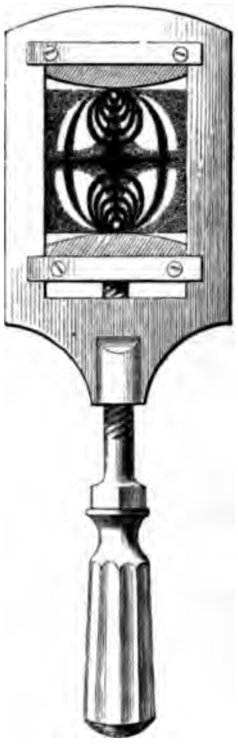


FIG. 268.—Colours of polarized light in compressed glass.

the analyser of his apparatus (disposed so as to show darkness); at each vibration he saw a bright line shine out, the brightness and colour of which depended on the mode of friction, and on its intensity."

The colours of polarized light, produced by the passage of a beam of this light through a thin crystalline plate, depend, as we have already seen, on the thickness of the plate; it varies, if the thickness itself varies. But for a certain thickness, the tint is uniform, because all the rays which compose the beam are parallel, and thence traverse the same space in the interior of the plate. If instead of a beam a conical pencil of polarized light is received on the plate, so that the axis of the cone is perpendicular to the surface of the plate, it is clear that the rays will pass through the interior of the crystal in paths which will be longer as their distance from the axis increases, and the tint of the plate, observed by means of an analyser, will no longer be uniform. We then see systems of coloured rings, the forms and tints of which vary according as we are dealing with a crystal with one or two optical axes, and according to the position of the polariscope in regard to the plane of polarization. The following is the manner in which the beautiful phenomena, which are partly reproduced in Plate VIII., are obtained. A tourmaline pincette or forceps is used (Fig. 270). This instrument consists of two metallic rings with a spring in the

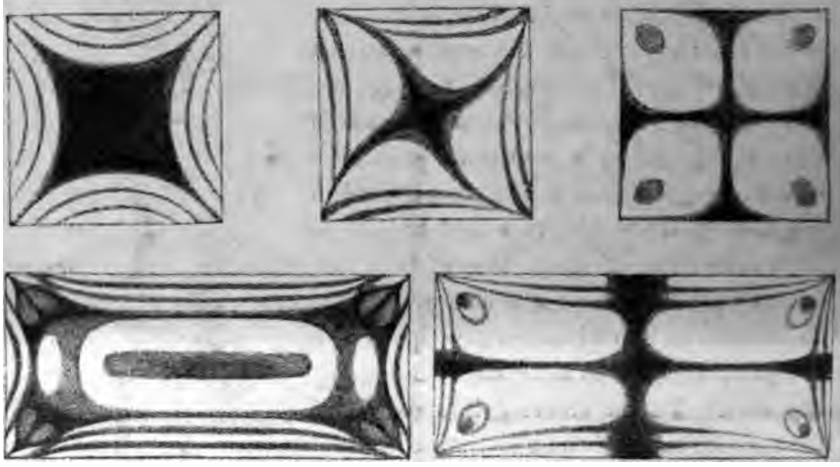
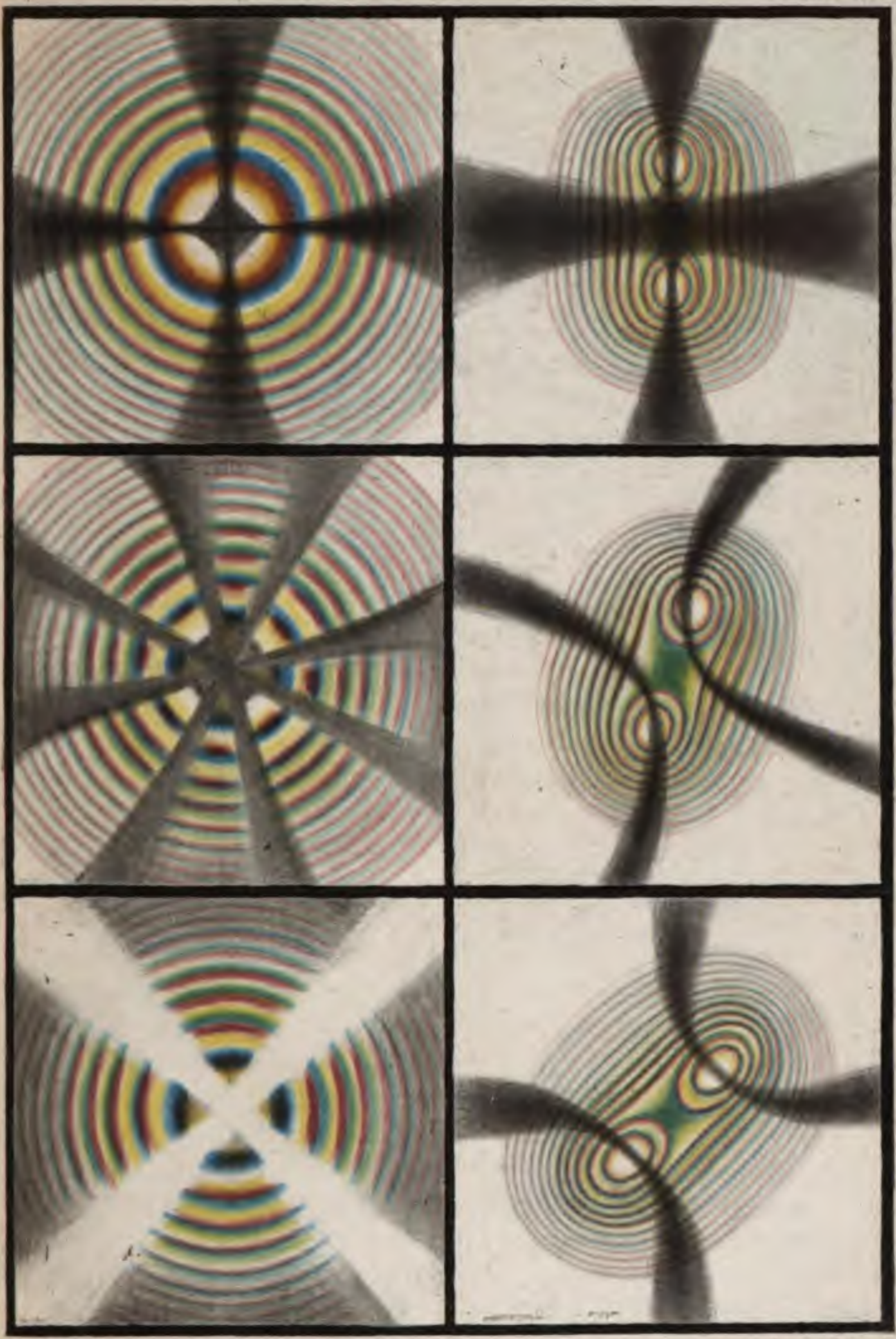


FIG. 269.—Colours of polarized light in unannealed glass.



D'après J. Silbermann

Digeon del et sculp

COLOURED RINGS

produced by doubly refracting prisms

WITH ONE & TWO AXES

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form of tweezers, which presses them together, and in each of which a plate of tourmaline is encased; each plate is capable of turning in its ring, so that, at will, all possible angular positions can be produced in regard to the axes of the two crystals. Between the two rings is interposed the thin crystallized plate, of Iceland spar for instance, fixed to a cork disc, which the pressure of the rings holds between the tourmalines. If we look through this system of three plates, we at once perceive the coloured rings. The plate of tourmaline turned towards the sky polarizes the light of the clouds, which, after having traversed this first plate, converges towards the eye in passing through the plate of spar and the second tourmaline. Let us suppose first that the two tourmalines are disposed in such a manner that their axes are perpendicular: the primitive plane of polarization is then parallel to the principal section of the tourmaline which serves as a polariscope. A series of concentric iridescent rings is seen traversed by a black cross (Plate VIII. Fig. 1). If the polariscope is then turned 90°, the axes of the tourmalines will be parallel, and the principal section of the polariscope will be at right angles to the plane of polarization. The black cross is then found to be replaced by a white one, and the iridescent rings show, at the same distance from the centre, colours complementary to those which they assumed in the first experiment. (Plate VIII. Fig. 3.) In the intermediate positions of the axes of the tourmalines, the first appearance gradually passes into the second; if the axes are inclined 45°, Fig. 2, Plate VIII. is obtained.

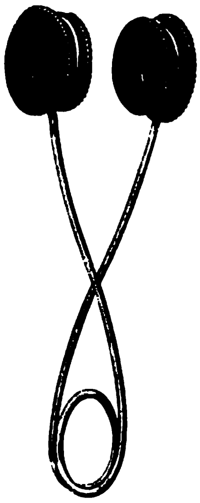
FIG 270.—Pincette of tourmaline.

These phenomena are presented in the case of white light. If homogeneous light is used, yellow light for instance, rings are obtained alternately bright and black, having crosses similar to those seen in the preceding experiment, the bright rings being of a yellow colour. Rings of the same kind would appear if the different colours of the spectrum were employed, and would be larger according to the refrangibility of the colour: for this reason the rings are iridescent when white light is employed, and this also is why the violet occupies, in this case, the outer edge of each ring in the first position of the polariscope.

In 1813 Brewster discovered the coloured rings produced by polarized light when it traverses thin plates of doubly refracting crystals: he saw them first in the ruby, emerald, topaz, in ice, and nitre; later, Dr. Wollaston observed them in Iceland spar. By studying these phenomena in the different crystallized substances Brewster succeeded in dividing doubly refracting crystals into two classes, viz. crystals with one axis and crystals with two axes; and this he effected by the following means:—Whilst, in the ruby, emerald, and Iceland spar, for example, he only observed a simple system of coloured rings, in nitre and topaz cut in a certain direction and observed through the tourmaline pincettes he observed a double system of rings, alternately black and bright, if the polarized light which traverses them is homogeneous, and iridescent, if this light is white. This phenomenon led Brewster to the discovery of crystals with two axes.

To observe the rings of which we speak, a plate of nitre is cut perpendicularly to the mean line of the two axes, and is placed between the rings of the tourmaline pincettes.

We then see one of the Figs. 4, 5, and 6 of Plate VIII. Fig. 6 represents the appearance when the plane of the axis of the plate of nitre is parallel to the primitive plane of polarization; Fig. 4 when these planes make an angle of 45°; lastly, Fig. 5 represents the rings produced in the intermediate position. From 45° to 90°, the same appearances are again produced, as also in each right angle, if the plate of nitre is caused to turn on itself.

With homogeneous light, rings are obtained alternately which are black and bright, the latter being of the colour of the light source.

If the plate remains fixed between the two tourmalines and the analyser is turned (that is to say, the tourmaline near the eye), the rings without changing their position gradually change in colour, and when the rotation is 90° or 270° these colours become complementary to those which the rings first assumed in the same position of the plate: the black crosses have been replaced by white ones.

We must stay here in our description of the phenomena produced by polarized light; they are most interesting, and the very enumeration of them would require many pages. The reader however will be glad to know that, for the expenditure of a few shillings and of some time, he may produce most of these beautiful phenomena for himself. The object which we have proposed to ourselves is rather to excite the curiosity of the reader and to induce him to undertake a more complete study of natural philosophy, than to give a precise notion of the causes of these phenomena; that is to say, to show what explanation they receive according to the undulatory theory. We cannot help however giving a *résumé* in a few lines of the important progress which that theory has made, under the influence of the discoveries which succeeded each other so rapidly at the beginning of our century.

In a preceding chapter we have noticed that luminous phenomena are due to the vibratory movement of the elastic medium called the ether. Phenomena of interference, inexplicable by the theory of emission, find the most simple and satisfactory explanation on the undulatory theory; but they tell us nothing as regards the *direction* in which the vibrations of ether take place. We can suppose with equal possibility that the oscillations of a molecule are affected either in the direction of the propagation of light, or in a direction parallel to the surface of the waves, or perpendicular to the luminous ray, or lastly, in any direction oblique to this ray.

But adopting the first hypothesis,—that which assimilates, so to speak, the luminous waves to sonorous waves,—it would be impossible to describe the transformation that a luminous ray undergoes, when it has traversed a doubly refracting medium, or when it is reflected at a certain angle from the surface of a polished body. Why, if the vibrations are longitudinal, should the polarized ray possess particular properties in certain planes? Why should these properties belong exclusively to certain sides of the ray? These objections gave a great blow to the undulatory theory when Fresnel conceived the idea of substituting for the hypothesis of longitudinal vibrations, that of transversal vibrations perpendicular to the direction of the luminous propagation. A ray of ordinary light therefore becomes one in which the vibratory movements are effected successively in all directions to the surface of the wave; hence its properties must be the same in all directions. But if this ray passes through a polarizer, on emerging the vibrations of which it is composed, instead of being effected in all directions, become parallel, and are all effected in planes perpendicular to the ray. The polarizer has, so to speak, sifted the vibrations of of common light: it has stopped or destroyed some, and has wed those vibrations only to pass which are in the plane of the principal section. More accurately, every vibration parallel to the principal section passes without alteration through the crystal, while every perpendicular vibration is destroyed: and all vibrations oblique to the two first are decomposed into others,—one parallel to the principal section of the polarizer, which passes; the other perpendicular, which is stopped. From this cause arise the properties of polarized light which we have described.

The con nences of the undulatory theory thus modified are very numerous: u n proved by experiment; or rather, the phenomena tion are explained, like those deduced from theory, a which is the most striking proof of the truth of the p ch constitute the undulatory theory.

Let us add now a few lines on the applications of polarized light in the study of the natural and physical sciences.

Arago used polarization by double refraction to construct a photometric apparatus based on the relative intensity of two images: an intensity, the law of which was enunciated by Malus. The same savant has indicated a means of distinguishing rocks under the sea which are hidden by the brightness of the light reflected from the surface. Looking through a Nicol's prism, the principal section having been carefully placed vertically, the reflected rays are extinguished; and the refracted rays being alone transmitted to the eye, reveal the presence of the submerged rocks.

Polarization enables us to know whether the light which comes to us from a substance has been reflected from its surface. It is in this way that the nature of the light of the heavenly bodies may be determined, which, like the moon and planets, simply send us the sun's rays; and it has been stated that the light of cometary masses is partly borrowed from the sun, as many observers have distinguished traces of polarization in a plane passing through the sun and the nucleus. The polariscope also is a valuable ally in eclipse observations. The light of the rainbow is polarized in a plane normal to the bow and passing through the eye of the observer. We shall learn indeed that the rainbow is formed of light reflected by the spherical drops of rain. Arago made use of polarization by reflection to discover the nature of various precious stones: having cut a small facet on the surface of one of them, he determined the angle of polarization, and noticed that it was exactly that of the diamond. Chromatic polarization is of great help in the study of crystals: it indicates whether a crystal has one or two axes of symmetry, as also the position of these axes in the crystal, &c.

Lastly, quartz and a great many liquids, solutions of sugar, solutions of tartaric acid and albumen, all have a property characterized by physicists as the rotatory power: a plate of quartz cut perpendicularly to the axis causes the plane of polarization of the rays which traverse it to deviate through a certain angle; and this deviation is different for rays of different colours. If the polarized light which has traversed the quartz is white, the colours which compose it will be destroyed in different proportions: hence a certain tint proceeding from the mixture of the rays which are not extinguished. This is the phenomenon of rotatory polarization discovered by Arago in 1811, and the laws of which Biot has studied experimentally.

Now these laws have furnished a valuable method in the arts called *saccharimetry*, by the aid of which the quantity of pure sugar contained in a solution of sugar can be discovered.

These phenomena therefore, which seemed at first only interesting in theory, can be brought to bear on important practical processes.

CHAPTER XVIII.

THE EYE AND VISION.

Description of the human eye—Formation of images on the retina—Distinct vision of the normal eye—Conformation of the eyes in Myopsis and Presbyopsis.

THE numerous and varied phenomena which we have just described, all relate to the propagation of light through different media, and to the modification it undergoes either in point of intensity or colour, when the conditions of the path followed by the luminous rays are changed. We have not occupied ourselves yet with the manner in which our organs are affected by all these phenomena, nor with the path followed by the light when it ceases to belong to the outer world and becomes an internal phenomenon.

How is this passage effected? by what transformation does a vibratory movement, such as that of ether waves, succeed in producing in man and other animals the sensation of sight? How do variations in the velocity or in the amplitude of the vibration produce corresponding variations in the intensity of light and colours of bodies?

This is a series of questions which science is far from having solved, and which moreover belong rather to the domain of physiology than to physics.

That which is known and which observation has investigated in a positive manner is the path of the luminous rays in the eye, from the instant when they penetrate that organ to the moment when they reach the nerves; the impression they then produce is transmitted to the brain and determines the sensation of sight. During this passage, the luminous rays obey, as we shall see, the known laws of propagation of light through media of variable form and density; we deal only with phenomena of simple refraction.

The eye is nothing more than a dark chamber, the opening of which is furnished in front with a transparent window, behind which there is a lens; and the back of which is covered with a membrane, which serves as a screen upon which the images of exterior objects are projected and reversed. We will now give a detailed description of this admirable instrument.

The eye is placed in a cavity of the skull known as the *orbit;* its form is that of a nearly spherical globe entirely covered by a hard consistent membrane, the resemblance of which to horn has caused it to be called the *cornea* where it is transparent in front, and elsewhere the sclerotic.

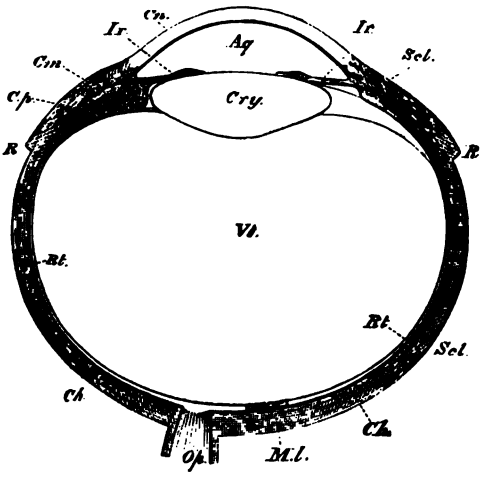

FIG. 271.—Horizontal section of the eyeball. *Scl.* the sclerotic coat; *Cn.* the cornea; *R.* the attachments of the tendons of the recti muscles; *Ch.* the choroid; *C.p.* the ciliary processes; *C.m.* the ciliary muscle; *Ir.* the iris; *Aq.* the aqueous humour; *Cry.* the crystalline lens; *Vi.* the vitreous humour; *Rt.* the retina; *Op.* the optic nerve; *M.l.* the yellow spot. The section has passed through a ciliary process on the left side, and between two ciliary processes on the right.

The cornea, in front of the eye, has a much more marked curvature than the sclerotic; it is like a very convex watch-glass.

Through the transparent cornea is seen a circular membrane, the colour of which varies according to persons and races; sometimes grey, light or dark blue, or sometimes a yellow brown. This membrane is the *iris,* a kind of diaphragm pierced in the centre by an aperture which is circular in man; this opening is called the *pupil.* Behind the pupil which is the opening of the dark chamber there is a solid lens; this is the *crystalline lens,* the outer face of which presents a less decided curve than the inner. The crystalline lens divides the cavity of the eye into two parts or chambers of unequal dimensions, as shown by Fig. 271. The anterior chamber, placed between the transparent cornea and the crystalline lens, is full of liquid, differing very little from pure water, and which has nearly the same refractive power; this liquid is called the *aqueous humour.* Between the crystalline lens and the back of the eye is the posterior chamber, which is filled with a transparent colourless substance having the consistence of a jelly, and rather more refractive than water: it is the *vitreous humour.*

A ray of light which penetrates into the eye traverses the following series of refractive media, before arriving at the back of the organ: the transparent cornea, aqueous humour, the crystalline lens, and vitreous humour. In each of these media, the light undergoes a particular refraction, and the whole deviation is such that it comes to a focus on the membrane which covers the posterior chamber of the eye. All the inner surface of the *sclerotic* is covered with a thin membrane, the *choroid.*

The choroid coat is lined internally with a layer of polygonal bodies containing pigments; these are called *pigment cells.* Inside these lies the *retina,* sections of which are given in the next figure.

Those parts of the eye that we have just described tend to the formation and reception of the images of objects; their functions are therefore passive. It is on the retina where these images are produced that the impression of light on the sensible part of the eye takes place. Behind the globe of the eye, the choroid and the sclerotic are pierced with a circular hole, which gives passage to the filaments of the optic nerves. This fasciculus or sheaf, on arriving at the interior of the eye, is spread out and extended over the whole surface of the sclerotic, forming a membrane immediately in contact with the vitreous humour.

Hence, then, we have a lens to throw an image; the eye is a "water camera," and the retina is the equivalent of the photographer's ground glass or prepared plate, where the vibrations of the ether are, in Professor Huxley's language, converted into a stimulus to the fibres of the optic nerve, which fibres when excited have the power of awakening the sensation of light in us by means of the brain. But it must not be forgotten that the fibres of the optic nerve are as blind as any part of the body; "but just as the delicate filaments of the ampullæ, or the otoconia of the vestibular sac, or the Cortian fibres of the cochlea, are contrivances for converting the delicate vibrations of the perilymph and endolymph into impulses which can excite the auditory nerves, so the structures in the retina appear to be adapted to convert the infinitely more delicate pulses of the luminiferous ether into stimuli of the fibres of the optic nerve."

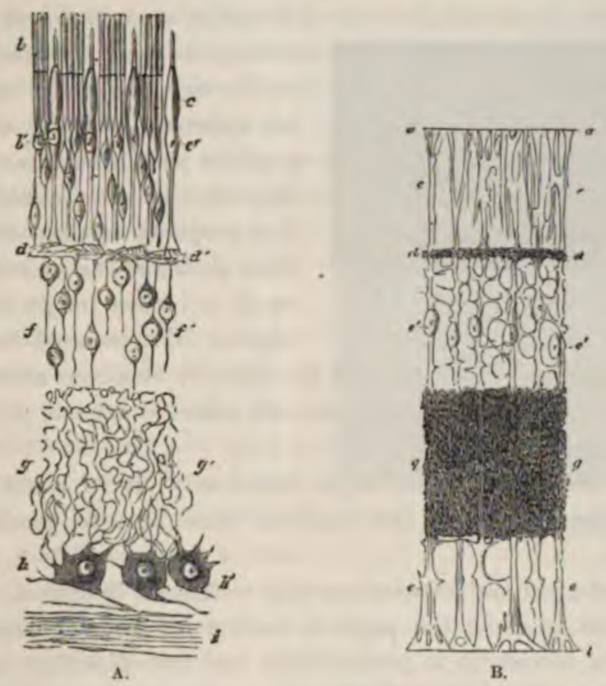

FIG. 271 A.—Diagrammatic views of the nervous (A) and the connective (B) elements of the retina, supposed to be separated from one another. A, the nervous structures—*b*, the rods; *c*, the cones; *b' c'*, the granules of the outer layer, with which these are connected; *d d'*, interwoven very delicate nervous fibres, from which fine nervous filaments, bearing the inner granules, *f f'*, proceed towards the front surface; *g g'*, the continuation of these fine nerves, which become convoluted and interwoven with the processes of the ganglionic corpuscles, *h h'*; *i i*, the expansion of the fibres of the optic nerve. B, the connective tissue—*a a*, external or posterior limiting membrane; *e' e'*, nuclei; *d d*, the intergranular layer; *g g*, the molecular layer; *l*, the anterior limiting membrane. (Magnified about 250 diameters.)

It is easy to account for the path of the rays of light which emanate from an object A B, and the manner in which this object forms its image on the retina. This lenticular system, composed of the transparent cornea and the crystalline lens separated by the aqueous humour, has its optic centre at the point *o* situated a little behind the crystalline lens (Fig. 272).

If the secondary axes, A *o* and B *o*, are taken, it is in their prolongation and at the point where they meet the retina, that the beam emanating from the points A and B converges; the intermediate points will form their images between the positions *a* and *b*. The images *b a* of the object will then be reversed. This result is one of the consequences of the laws of refraction and of the path of rays through lenses; but it has been proved by direct observation. Thus, by taking the eye of an animal just dead and freeing it from the strata of fat with which the ball is enveloped, the sclerotic is pared off at its posterior part, in such a manner as to render it translucent: the eye thus prepared, and exposed to daylight, shows on the sclerotic a very small and clear image of exterior objects. The reversed image of a candle can also be seen through the sclerotic of albino animals; the absence of colouring pigment in this sclerotic renders it naturally translucent.

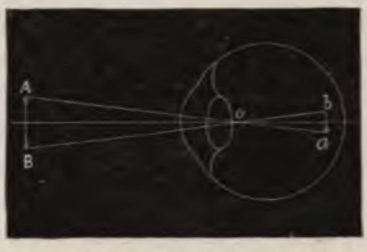

Fig. 272.—Formation of images in the normal eye.

The iris acts as a diaphragm, which only allows cones of light, having the aperture of the pupil for their base, to penetrate into the eye.

But the iris can be spontaneously contracted or dilated, in such a manner as to cause the pupil to become narrower or larger. This automatic movement is produced in the first direction when the brightness of the light received by the eye increases; and in the second direction if this brightness diminishes. The same thing occurs when the eye looks at objects situated at different distances; the pupil enlarges for distant objects and contracts for objects nearer the eye.

Look at the eye in a looking-glass when you hold it at a certain distance, and examine the dimensions of your pupils; then rapidly draw the mirror nearer without moving the pupil: you will see the iris slowly get narrower.

The eye being thus assimilated to a system of lenses, it may appear singular that it can be used to see clearly so many objects situated at such varied distances. It cannot be doubted that in order that the vision be distinct, the object must make its clear image on the retina itself.

It is necessary then, when the distance changes, that the focus should change also, so as always to coincide with the surface of the nervous membrane. This fact is explained by saying that the eye accommodates itself to distances. But by what mechanism does the eye in this way keep its property of clearly distinguishing objects? For short distances, the narrowing of the pupil; and for long ones, a change in the form of the crystalline lens which diminishes its converging power: such are the two movements submitted to our will, but made without our knowledge, by the aid of which physicists explain the adaptation of which it is capable. There is an inferior limit to the distance of objects that we try to see clearly: this is the limit of distinct vision, which varies with individuals and with age, between 15 to 20 centimetres. In a normally constituted eye, there is no superior limit.

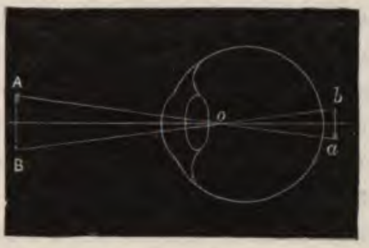

FIG. 273.—Formation of the image in the eye of a long-sighted person.

The conformation of the eye may be such, that the limit of distinct vision may be much greater than that of which we have just spoken. This affection, which is met with especially in old people, obliges them to hold a book at a great distance to read it clearly. That is because the image is formed beyond the retina, so that the convergence of the rays emanating from a luminous point does not fall on this membrane, whence a confused impression results. By taking the object to a distance, the focus is brought forward, and vision becomes more distinct. Persons with this defect of sight are *long-sighted:* this is attributed either to the diminution of the crystalline lens or to a rigidity which does not permit of adaptation to small distances, or lastly to a flattening of the globe of the eye; *near-sighted* people have the opposite defect. The distance of distinct vision is much shorter for them than for normal sight, and at great distances the sight is always confused. This arises

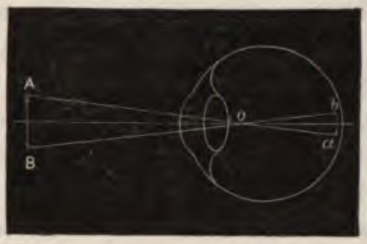

FIG. 274.—Formation of the image in the eye of a short-sighted person.

from an opposite cause to that which produces long-sight: the focus or the image of a luminous point is formed *in front* of the retina. The extreme convexity of the crystalline lens and the large diameter of the globe of the eye are the most ordinary causes of short-sightedness. This defect is acquired by habit: literary and office men, and people whose occupations oblige them to look closely at small things, are frequently subject to this infirmity.

Many physicists have inquired why the images of objects, being reversed on the retina, are seen in their real positions; that is to say, upright. To explain this apparent singularity, hypotheses more or less ingenious have been suggested. But the image projected on the retina is not an object that we might examine, as if we possessed another eye behind the retina. In truth, outer objects and ourselves, our own bodies, are seen by us in their exact relative positions: this is all that is necessary, and when we say that we see an object, a tree for example, upright and not inverted, that simply means that its top and its base appear to us, the first to be raised in the air, the other touching the ground, absolutely in the same direction as our own head and feet in our normal position. If, by a particular disposition of one eye, similar to that of certain lenses, the images were made upright on the retina, it does not appear doubtful to us that our perception would not be changed: in order to make it otherwise, it would be necessary that there was an exception for the image of our body, which is beyond supposition.

The impression made by light on the retina lasts a certain time, which accounts for our seeing under the form of a luminous line a bright point which moves rapidly: thus the end of a stick, being lighted, by rapid turning takes the form of a circle of fire. Some experiments made by M. Plateau prove that the mean length of sensation is eight-tenths of a second; that the light must persist a certain time, in order that the impression produced arrive at its maximum, and that the length of this maximum is in the inverse ratio of the brightness; lastly, that the length of the total sensation increases with the intensity of the light.

BOOK IV.

HEAT.

BOOK IV.

HEAT.

CHAPTER I.

DILATATION.—THERMOMETERS.

Sensations of heat and cold; causes of error in the perception of the temperature of bodies—General phenomena of dilatation and contraction in solids, liquids, and gases—Temperature of bodies—Thermometers based on dilatation and contraction—The mercurial thermometer—Alcohol thermometer—Air thermometers; metallic thermometers.

ALL known substances, whether solid, liquid, or gaseous, appear to the touch more or less warm or cold. This impression, as daily experience shows, depends as much on the particular disposition of our organs as on the condition of the bodies themselves; moreover it may chance that they do not produce in us any sensation of heat; in a word, they may appear neither hot nor cold.

The same body, when we touch it at different times, may also produce in us different and even opposite sensations, either because it is really in the interval warmed or cooled, or because our organs have undergone analogous modifications; or, lastly, the two causes to which we have here referred may have simultaneously contributed to the differences of impression. Anyone can easily find examples of the influence of these two causes, and we can understand how difficult it would be to appreciate variations in the temperature of bodies, if the basis of this appreciation were only the personal sensations produced by contact, or at a distance. Let us suppose, for example, that we hold our right hand for some time in a vessel of cold water, and our left in one of very warm water, and that we afterwards plunge them both at the same time into a third vessel filled with lukewarm water; we shall undergo simultaneously two opposite sensations, one of heat, the other of cold, both proceeding, nevertheless, from the same body in the same condition.

Another example of the difficulty which we have pointed out exists in the fact that the outer air appears to us cold if we leave a warm room; and, on the contrary, the same air seems warm when we come out of a cool cave. On entering a well-warmed room in frosty weather we declare that the temperature is unbearable; nevertheless, in warm weather, if the air suddenly cools, we shall shiver in the same temperature which would appear excessively high in winter. This is because our organs, which are gradually habituated to the cold or heat, with difficulty undergo the quick transitions which determine in them more intense sensations. It is not therefore possible to make use of such variable impressions in the determination, however inexact, of the thermic condition of bodies.

Hence the necessity of finding among the effects which result from the variations of temperature in solids, liquids, and gases, a phenomenon sufficiently general and constant to be used as a point of comparison in studies of this nature; that is to say, a phenomenon, the variations of which can be verified and measured, without the necessity of the intervention of the personal impressions of the observer. Now, physicists have ascertained the fact—general with one or two exceptions, some apparent, others real—that all bodies, whatever their physical state, on being heated, increase in volume or dilate, and on being cooled contract or diminish in volume. We will first describe some experiments which demonstrate this phenomenon, in solids, liquids, and gases.

If we take a metal sphere and ring of the same substance, of such dimensions that when they are at the same temperature the sphere can just pass through the ring, and if the ball alone be now heated and placed on the ring, it will no longer pass through, which proves that it has been expanded by heat; but if it is allowed to cool and return to its original condition, it again passes through. If, on the other hand, the ring is warmed, the metal sphere passes freely through the opening, whence it may be concluded that the ring has been enlarged by the heat. But, if the ring and the sphere are heated at the same time, and equally, both increase in volume to a like extent, and they preserve the same relationship as regards size as at the commencement. This little apparatus is known as S'Gravesande's ring, from the Dutch physicist who invented it. Sometimes it takes another form (Fig. 276); for the sphere a metallic cone is substituted, on which the ring slides to different heights according as the ring or the cone is alone heated. If the increase of temperature is the same for the cone and the ring, that is to say, if both are uniformly heated, although separately, the ring descends on the cone to an invariable position. This last fact furnishes us with an important indication as to the manner in which vases which are cylindrical, conical, or of other forms, are dilated. Their change of volume takes place as if the vase were filled with the substance which forms the envelope: its interior capacity varies, as the volume of the solid nucleus of which we speak itself varies, under the same thermic conditions.

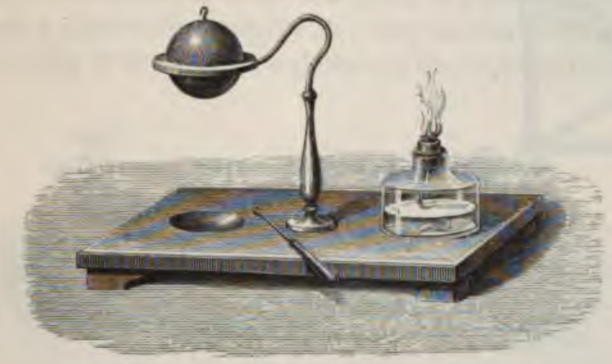

FIG. 275.—S'Gravesande's ring. Expansion of solids by heat.

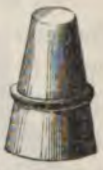

FIG. 276.—Expansion of solids.

Bodies expand by heat equally in every direction, so that a metallic rod having the form of a parallelopiped increases in each of its three dimensions, width, length, and thickness. Hence there are three kinds of expansion—cubical, superficial, and linear expansion. The last is proved by means of the apparatus represented in Fig. 277. A metallic rod is fixed at one of its extremities, and when heated along the whole of its length it dilates freely at the other extremity, which presses against the little arm of a bent lever so that the index forming the large arm of the lever describes, on a graduated scale, an arc which is larger as the relation of the lengths of the two branches increases. The smallest amount of expansion of the rod is thus rendered perceptible.

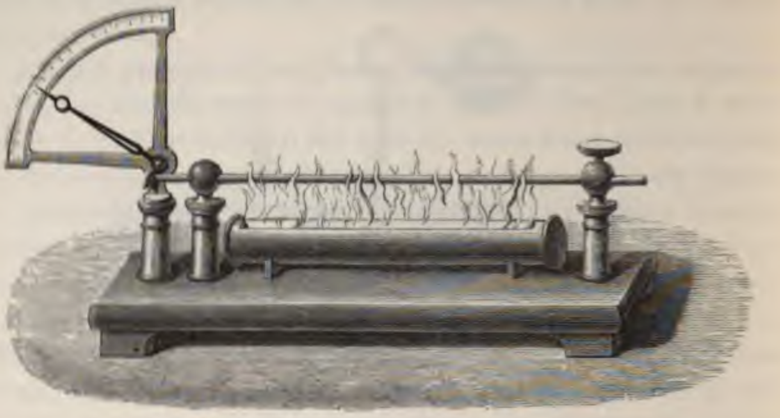

FIG. 277.—Linear expansion of a solid rod.

Variation of temperature produces much more decided variations of volume in liquids than in the greater number of solids. The following is one of the means which is used to demonstrate the expansion of liquids.

We take a glass bulb, to which is attached an open tube of small diameter; we fill it with the liquid to be experimented upon, and mark upon it a line *a* to indicate the position of the liquid in the tube (Fig. 278). Then, plunging the bulb into water warmer than the liquid, the movement of the latter can be easily followed in the tube. At first the level is seen to descend from *a* to *b*; which arises from the expansion of the glass envelope, which responds to the first action of the heat. Hence its capacity is increased, before the liquid within can compensate for this augmentation by its own expansion. But after a short time the apparent contraction ceases, and the liquid gradually rises to, say, the point *a′*, where it remains if equilibrium has been established. If the apparatus is now cooled, the liquid will be seen to descend gradually, until at last it assumes its original height.

Different liquids do not expand equally under the same conditions, but, with about one exception, to which we shall soon advert, they all increase or diminish in volume, according as they are heated or cooled.

Again, gases are still more expansible than liquids: if we place near the fire a closed bladder half filled with air, we observe that it gradually swells out; the air which it contains therefore increases in volume by the action of heat. The expansion of air, or any other gas, under the influence of an increase of temperature, may be proved by other means If we take a glass bulb provided with a long capillary tube open at its extremity (Fig. 279) and filled with the gas the expansion of which we

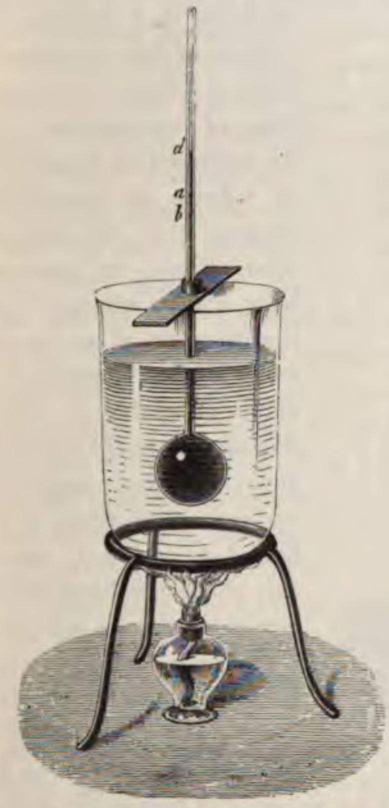

FIG. 278.—Expansion of liquids by heat.

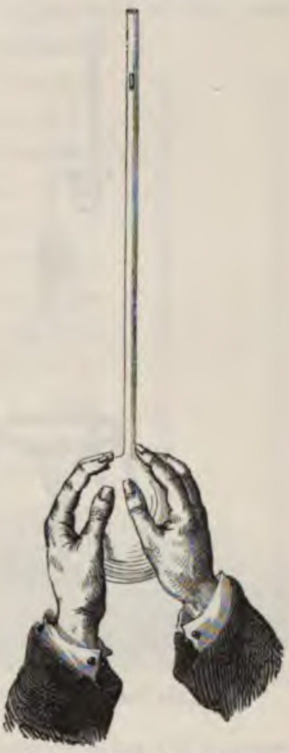

FIG. 279.—Expansion of gases by heat.

desire to prove, and which is separated from the outer air by an index of mercury; immediately that the bulb is slightly warmed, by the contact of the hands for example, the interior gas also becomes warm, expands and drives the index from the reservoir. When the gas has cooled, its volume diminishes, and the index again assumes its original position. By using a doubly bent tube (Fig. 280) containing some liquid at the lower curve, the expansion is seen by the rising from *a* to *b* of the liquid in the arm most distant from the bulb, whilst the level descends in the other.

Let us confine ourselves for the present to the phenomenon which, with but two or three exceptions, some apparent and others real, is general: solids, liquids, and gases are expanded when their temperature rises and are contracted when it falls. A given and invariable quantity of matter of a certain substance corresponds in a particular thermic condition to a determined volume of the substance; hence it follows that variations of temperature can be measured by variations of volume or expansion. Suppose that we take a solid, liquid, or gaseous body, and so arrange that the quantity of matter of which it is composed remains invariable, or, if we like, that its weight remains always the same; and that we endeavour, when it is heated or cooled, to measure either its volume or the variations of its volume. Now, these variations will serve as measures of the heating and cooling of the body, so that whenever it possesses the same volume, we shall be certain that it is in the same thermic condition; in a word, that it is at the same temperature.

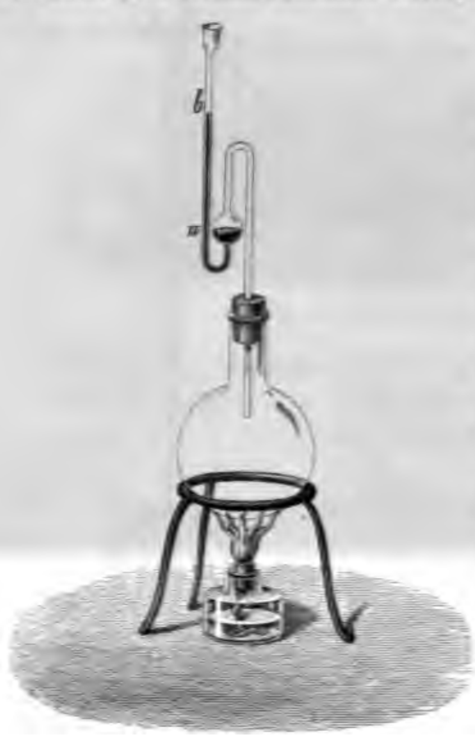

FIG. 280.—Expansion of gases.

The *temperature* of a body is, therefore, a particular state corresponding to a determined volume of this body. It is said that the temperature rises when the body gets warmer, and consequently, with the exception of which we shall presently speak, when it is expanded; its temperature, on the contrary, falls if the body is cooled, and therefore diminishes in volume.

All instruments which indicate and measure the variations of their own temperature, and, with more or less precision, those of the media in which they are plunged, are called *thermometers*. Contrivances of this kind are numerous, and we shall learn as we proceed that the construction of some of them is based on other principles than those of the expansion and contraction of bodies; but the indications which they give all relate to those of a thermometer which it is convenient to take as a standard or type for all others. We speak of the mercurial thermometer, which we shall describe first.

The mercurial thermometer consists of a glass tube of very small diameter, which is closed at one end and terminated at the other by a spherical or cylindrical reservoir (Fig. 281). The reservoir, and a portion of the tube enclosing some perfectly pure mercury, together with the rest of the tube, are entirely void of air and every other gas. As the interior capacity of the tube is only a very small fraction of the capacity of the reservoir, the least variation of volume in the latter is made apparent by a considerable change in the height of the mercury in the tube. In order to measure these variations, it is convenient to mark on the tube of the thermometer two points which correspond to two different temperatures, both fixed and invariable, and to divide into a certain number of equal parts the total increase of volume that the mercury is subjected to on passing from the lowest of these temperatures to the highest. As experiment has shown that ice always melts at the same temperature, and that the temperature of the steam of boiling water is likewise constant when the barometric pressure is at 760 mm. or 30 inches, these two fixed temperatures are the most convenient to use as fixed points for the graduation of the mercurial thermometer. The following is the method by which this graduation is effected:—

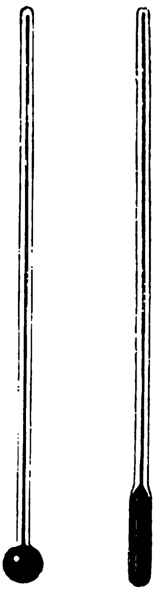
FIG. 281.—Reservoir and tube of the mercurial thermometer.

The reservoir and part of the tube are plunged into a vessel filled with pounded ice, and pierced with holes at the bottom, so that the water which might acquire a higher temperature than that of the melting ice, can freely escape (Fig. 282). The level of the mercury having become stationary, a line is marked on the stem: this point is the *zero* of the graduation.

thermometer is then placed in the position indicated in Fig. 183, that is to say, in a bath where it is completely surrounded by steam of boiling water. The bath consists of a double ... with plates, wherein the steam circulates before escaping ... so that the temperature of the internal space is not cooled by the exterior wall. Here again when the mercury becomes stationary, a horizontal line is marked on the stem. At this point (Fig. 183) the number 100 is marked, if, as we have said, the barometric pressure is at this moment at 760 millimetres, which the manometer with bent limbs seen to the left of the instrument indicates.[1]

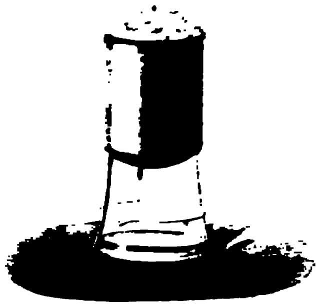

Fig. 182.—Determination of the zero of the centigrade thermometer; temperature of fusion of ice.

If the interior of the tube is perfectly cylindrical, which must be ascertained before blowing the bulb of the thermometer, it is evident that, if we divide the interval which separates the zero of the melting ice from the point 100, corresponding to the temperature of boiling water, into 100 equal parts, each of these will indicate equal capacities, and when the level of the mercury traverses them successively equal dilatations of the liquid. These divisions, which are called degrees, form the scale of temperatures, which can be extended below 0 and above 100 for the measure of temperatures lower than that of melting ice or higher than that of boiling water. The divisions are sometimes engraved on the tube, sometimes on a lateral tube fastened to the thermometer tube, and sometimes again are marked on the frame to which the instrument is fixed (Fig. 184).

The Centigrade scale is not the only one which has been adopted for the graduation of thermometers; but it is the most generally adopted, and the only one which is used at the present day in France and in a great many other countries. Its invention is attributed to a Swedish *savant*, André Celsius, who lived in the eighteenth century.

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[1] If the barometric pressure is not 760 millimetres at the time of the experiments, the level of the mercury will no longer indicate the fixed point where 100 ought to be marked. It has been determined that the difference is a degree centigrade (that is, the hundredth part of the dilatation between the point of fusion of the ice and that of boiling water) for a pressure which differs 27 millimetres, more or less, from 760, so that 101 must be marked if the pressure is 787 millimetres, and 99° if, on the other hand, it is only 733 millimetres. Between these limits a proportional correction is made for the excess or diminution of pressure.

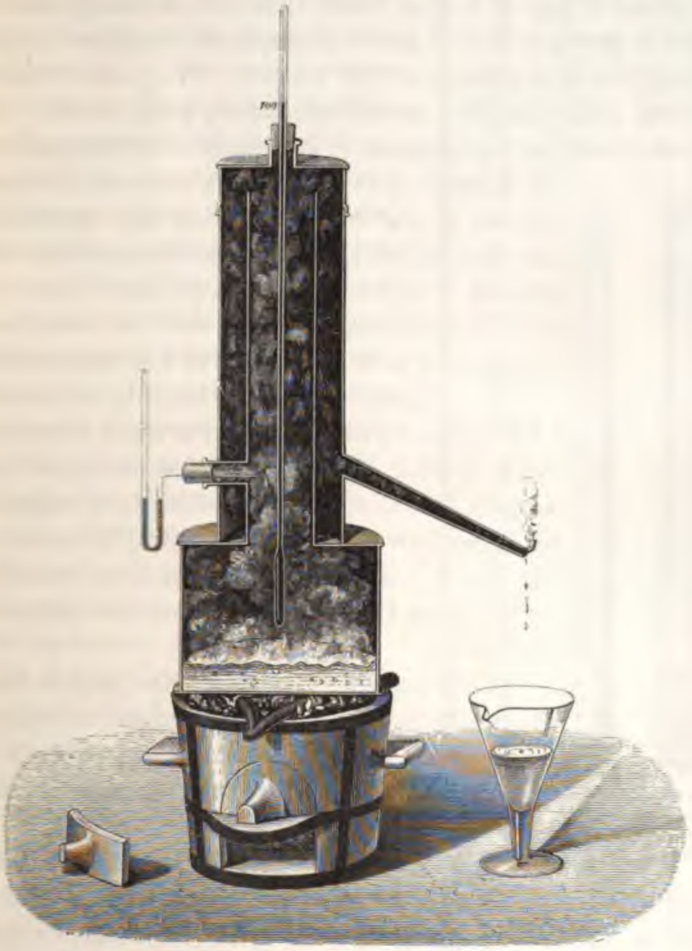

FIG. 283.—Determination of the point 100, the temperature of boiling water under a pressure of 760 millimetres.

The scale of Réaumur divides the intervals between the two same fixed points, melting ice and boiling water, into eighty degrees. A very easy calculation converts centigrade degrees into Réaumur's degrees; it is sufficient to add to the first number its quarter: thus 28° R. equals

28° + 7° or 35° C. If you take a fifth from a centigrade temperature, you have the same temperature expressed in Réaumur degrees: thus, 35° C. = 35° − 7° or 28° R.; 32° C. = 25°·6 R. In Fahrenheit's scale, which is used in Germany, England, and the United States, one of the *fixed* points is that of boiling water, as in the preceding scales; but the other corresponds to a lower temperature than that of melting ice, viz. that of a mixture of ice and salt. The zero is therefore very low. Fahrenheit has marked the boiling point at 212°. As it has been found that the temperature of melting ice corresponds to the 32nd degree of this scale, it follows that the hundred degrees of the centigrade scale are equivalent to 180 degrees Fahrenheit; hence the conversion of any number of degrees from one of these scales to the other becomes easy. If we wish to know, for example, what is the equivalent of 120 degrees Fahrenheit in centigrade degrees, we begin by deducting 32, which gives 88, of which the $\frac{5}{9}$ is taken, the resultant being 46° 66 C. On the other hand, having the temperature 45° C. to convert into divisions of Fahrenheit's scale, the $\frac{9}{5}$ are taken, which gives 81° F. above melting ice; this is marked 32°, as we have before seen: 81° + 32° or 113° F. thus becomes the result of the conversion.

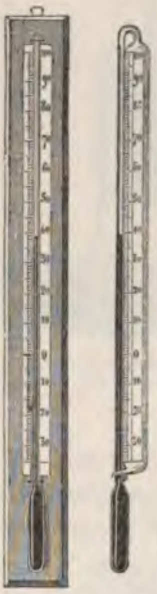
FIG. 284.—Centigrade thermometers with their graduated scales.

Delisle's scale is also used, principally in Russia: the boiling point is marked 0°, and the melting point of ice 150°. Nothing is more simple than to convert a temperature marked on this scale into any of the three others.

Care must be taken, when a temperature is stated, according to one or other of the graduations, to indicate whether it is higher or lower than that marked by zero. Physicists do this by considering temperatures higher than 0° as positive and placing the sign + before them, and temperatures lower than 0° as negative, distinguished by the sign −. These conventionalities once adopted, similar rules to those of the positive and negative algebraic quantities apply for operations effected on numbers expressing temperatures where they are combined by means of addition and subtraction. But it is necessary to give to each of these numbers its true meaning, and to abstain from attributing to it an absolute value which it does not possess. Thus we can only say, that a temperature is double or triple of another, or at least, if we use these expressions, nothing must be inferred as to the quantities of heat which correspond to them. This simply signifies that the expansion of the mercury above the fixed starting point, or zero, is in this case double or triple of the total expansion corresponding to the second elevation of temperature. In a word, we must not forget that the unit of temperature—for instance, the centigrade degree in the centesimal scale—represents an expansion of the mercury contained in the reservoir of a thermometer, equal to the hundredth part of the total dilatation which the same liquid would undergo, on passing from the temperature of melting ice to that of boiling water.

The thermometer which we have just described is based on the expansion of mercury, that is to say, of a liquid contained in a glass envelope. But when, by a variation of temperature, the volume of the liquid changes, the capacity of the envelope changes also. If these expansions or contractions of the mercury and the glass were equal, as they are made in the same direction, the level would not vary, and therefore it would give no indication. In reality, mercury expands seven or eight times more than glass, and this fact renders the mercurial

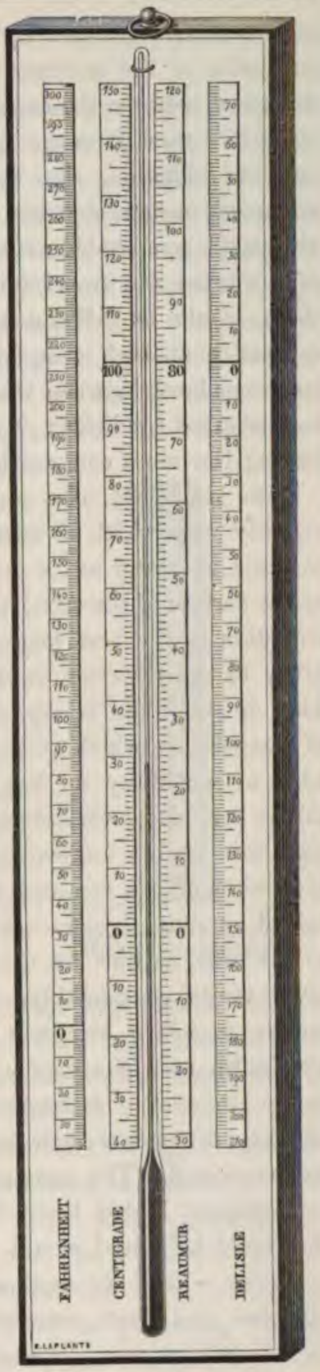

Fig. 285.—Thermometrical scales.

thermometer possible. But from this we learn that it is not the expansion of the mercury which causes the level to vary, but the difference between the expansions of the liquid and that of the envelope; in a word, it is the apparent dilatation of the mercury, not its absolute dilatation. But it is no less evident that the different thermometers, constructed and graduated as we have just stated, must always be comparable between themselves, whatever the dimensions of the tubes and reservoirs, and the quantity of mercury in each of them. Only, as different kinds of glass are not equally expansible, especially at high temperatures, in order that there should be correspondence between the indications of the instruments submitted to the same conditions, it is necessary that they be made of glass having the same composition.

The sensibility of a mercurial thermometer, that is to say, the rapidity with which it assumes the temperature of the surrounding medium, is greater as the mass of mercury in the reservoir is less, and as the surface of the envelope is greater. In order to fulfil this second condition in the best manner, the cylindrical or even spiral form is given to the reservoir, as it is preferable to a spherical bulb. This kind of sensibility is especially desirable for ascertaining variations of temperature which quickly succeed each other. There is another kind of sensibility no less useful than the first: it is that which allows very slight variations of the level, corresponding to very slight variations in the temperature, to be manifested, so as to allow the indication of the smallest fraction of a degree. This quality is obtained by giving larger capacity to the reservoir, and small diameter to the tube, so that for the expansion indicated by one degree the level varies considerably. Mr. Walferdin has constructed thermometers, to which he gives the name of *metastatic*, in which the hundredth part of a degree can be detected: whenever these instruments are used, it is necessary, on adding or taking away from the mercury, to regulate their course for the variations of temperature to be ascertained. The mercurial thermometer cannot be employed for temperatures higher than 360° above zero, because at this point the liquid boils and would break the tube. In like manner, below − 35° or − 36° the mercury is near the temperature at which it solidifies, and then contracts irregularly, and would thus furnish inexact indications. Beyond one or other of these limits, thermometers of a different kind, which we will hastily describe, are employed.

Let us commence with the alcohol thermometer, which is used to measure very low temperatures. This instrument does not differ in form from the mercurial thermometer; but it is graduated by comparison with a standard thermometer of the first kind, that is to say, the two tubes are plunged simultaneously into baths, the temperature of which is made to vary. The points at which the level of the alcohol becomes stationary are marked for each temperature which is determined from the mercurial thermometer, and the intervals are divided into as many equal parts as there are degrees from one to the other. But, even with these precautions, it is seldom that alcohol thermometers agree between themselves, or with the standard thermometer, which is explained by the irregularity of the expansion of this liquid at different temperatures. For lower temperatures than that of melting ice, it would be preferable to use thermometers filled with common ether, as this dilates with much greater regularity than alcohol.

Thermometers are also constructed of gas, based for example on the expansion of air. Fig. 286 represents two of these instruments, the first that were invented for the measurement of variations of temperature. Galileo invented the first: it consists of a tube and reservoir, enclosing a small liquid column or index, A, which separates the air of the reservoir from the outer air; as the temperature increases, the air contained in the bulb of the thermometer is warmed, dilates, and forces the index towards the open end of the tube. The other instrument is also formed of a tube and reservoir similar to the first, but its open end is immersed in a liquid contained in an open vessel; by cooling, the air decreases in volume, and its elasticity becomes less, so that the liquid, which is always submitted to the exterior atmospheric pressure, rises to a greater or less height in the tube. This instrument, which was much in request during the last century, was invented by a Dutchman named Cornelius Drebbel. These two thermometers are now graduated by

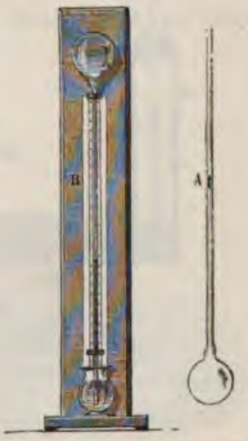

FIG. 286.—Air thermometers of Galileo and Cornelius Drebbel.

comparison with a mercurial thermometer. The points are marked at which the liquid becomes stationary at two different temperatures, and the interval is divided into as many equal parts as it comprises degrees. But they are both also affected by changes of atmospheric pressure, and are therefore not capable of much precision; their chief value consists in the rapidity of their indications.

Leslie and Rumford invented two thermometers based on the expansion of air, but not possessing the same inconveniences as the preceding; in other words, they are uninfluenced by pressure. They both consist of a tube, bent twice at a right angle, and terminated at each extremity by a bulb or reservoir. In Leslie's thermometer (Fig. 287) the tube encloses a column of sulphuric acid coloured red; the level is the same in each limb, when the temperature of the two bulbs is equal; this common level is marked 0. If now one only of the reservoirs is warmed, the air which it contains, in expanding, presses against the liquid; the level of the corresponding limb falls to *b*, whilst it rises in the other to *a*; and the height above zero marks the differences of temperature of the reservoirs, if this instrument has been graduated by comparison with a mercurial thermometer.

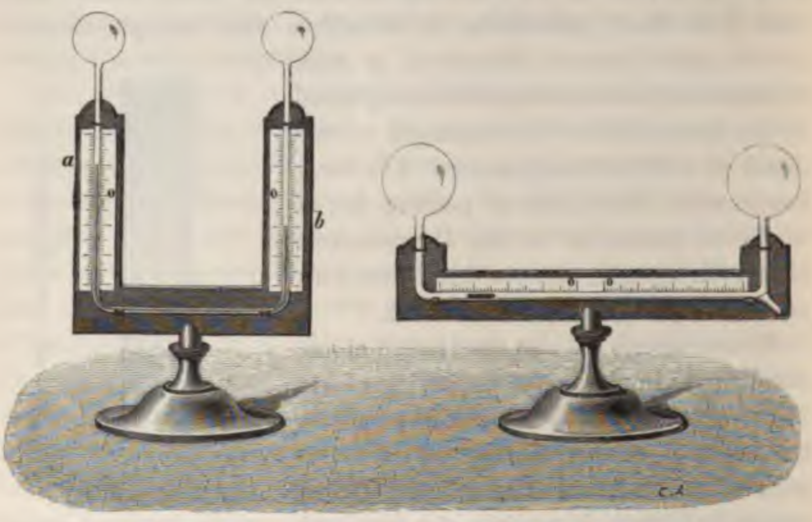

FIG. 287.—Differential thermometers of Leslie and Rumford.

Rumford's air thermometer differs from the preceding, inasmuch as the liquid column is replaced by an index which occupies the centre of the horizontal portion of the tube, when there is equality of temperature between the two reservoirs. If one of these is warmed more than the other, the expansion of the air causes the index in the horizontal part of the tube to move towards the colder bulb, and the difference of the temperature is measured by the number of divisions which this index passes over from zero.

These two instruments thus mark differences of temperature, and they are therefore known as *differential thermometers.* But they can also indicate absolute temperatures, if the graduation has been effected with this object in view.

The expansion of solid bodies may also be employed to measure temperatures. The instruments which we have described above are based on the unequal expansion of liquids, gases, and of the vessels which contain them; this inequality, perceptible in liquids, becomes considerable in gases. The construction of the metallic thermometers represented in Figs. 289 and 290 depends on the inequality of expansion of different solid bodies. Two metallic plates—for example, one of copper and the other of zinc soldered together lengthways, so as to form a straight bar, expand unequally when the temperature is raised; the bar then bends, as in Fig. 288; the zinc, which is the more expansible of the two metals, forms the convex side, and the copper the concave. When the bar has returned to its primitive temperature, it assumes its rectilinear form, to bend again in the contrary direction if it is afterwards subjected to cooling.

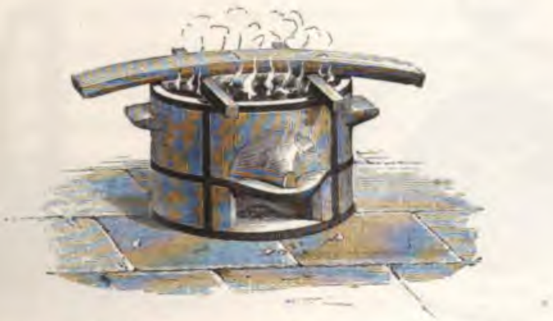

FIG. 288.—Unequal expansion of two different metals for the same elevation of temperature.

The metallic dial thermometer (Fig. 289) is composed of a curved plate of copper and steel soldered together; one of the extremities of this is fixed, while the other is supported by the small arm of a lever, the large arm of which, in the form of a toothed sector, works in the pinion of an index. Variations of temperature increase or diminish the curvature of the plate, and thus cause the lever and thence the index to move, sometimes in one direction and sometimes in the other. The dial is divided into degrees, by observing the indications of a mercurial thermometer. In Bréguet's metallic thermometer (Fig. 290) the plate is formed of three ribbons of silver, gold, and platinum, soldered together and formed into a spiral: the silver, being the most expansible of the three metals, forms the inner surface of the spiral. This is suspended vertically, and its lower extremity supports a horizontal index, which moves over the divisions of the dial. When the temperature rises, the curvature of the spiral diminishes under the influence of the greater expansion of the silver, and the needle moves in one direction: it moves in the contrary direction if the temperature falls. As the bulk of the spiral is extremely slight, it very rapidly acquires equilibrium of temperature with the surrounding air. Bréguet's thermometer is therefore very sensible, and useful for noting rapid variations of temperature.

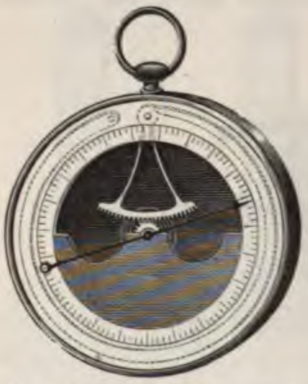

FIG. 289.—Metallic dial thermometer.

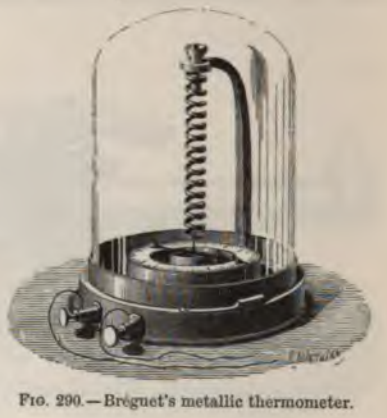

FIG. 290.—Bréguet's metallic thermometer.

We can only allude to *pyrometers*, which instruments are used for measuring very high temperatures, such as those of blast-furnaces, forge-fires, &c.; some are based on the expansion of solids, others on the contraction of clay. The trials which have been made in order to compare the indications of pyrometers with those of mercurial thermometers have not given very accurate results. When great precision is desired, air pyrometers are used for measuring high temperatures, a description of which will be found in more detail in treatises on Physics.

The various thermometers which we have recently described determine the variations of their own temperature, by the different expansions and contractions of their own substance. But the object which is proposed in constructing them is to measure the temperature of various media, whether solid, liquid, or gaseous—which in each instance requires particular precautions.

If it is a question of the temperature of the air or a gas, or again of a liquid, the thermometer is immersed in it; and if the instrument be of great sensibility, if its mass be very small in comparison with that of the medium, the temperature indicated by the thermometer, when the level of the mercury or the index is at rest, may be taken without sensible error for that of the medium itself. If it is a question of a solid body, a cavity large enough to receive the reservoir of the instrument is made, or, still better, this cavity is filled with mercury; after a short time, the temperature of this liquid is in equilibrium with that of the body, and the thermometer is then immersed. It is always necessary that the mass of this be very small compared with that of the body; indeed, as there is exchange of heat between them, the indication no longer relates to the original temperature of the body, but to that which is established at the end of this change, and on the hypothesis that the mass of the instrument is very large, the difference would be considerable. Hence it is evident, that this cause of error can never be entirely avoided; the effects can only be lessened, in order that the result may not be perceptibly altered.

CHAPTER II.

MEASURE OF EXPANSION.

Effects of variations of temperature in solids, liquids, and gases—Applications to the arts—Rupert's drops—Measure of the linear expansion of solids—Expansion of crystals—Contraction of iodide of silver—Absolute and apparent expansion of liquids—All gases expand to the same extent between certain limits of temperature.

A BODY expands when its temperature increases: this is the universal fact which we have stated, and which is employed to measure changes of temperature. But to what extent does the volume increase, and by what fraction of the primitive volume is it increased for one degree of the centigrade thermometer? Does this fraction vary in different substances, and does it remain the same at every temperature? Such are the questions which naturally present themselves to physicists when they have determined by observation the effects of variation of temperature. Before indicating the results at which they have arrived, let us show by a few examples the practical utility of the precise knowledge of these effects, and the necessity which often arises of correcting or foreseeing them.

If a fragile body which is a bad conductor of heat is subjected to quick changes of temperature, the effect produced will be the breaking of the body. Thus, if a red-hot bar is placed on a piece of cold glass the glass cracks; the same thing happens with a piece of very hot glass if it is suddenly placed in contact with a piece of cold iron. In the first instance, sudden expansion is produced in the portions of the glass touched by the hot iron, and the surrounding portions, which have not had time to become warmed, break violently from the first—hence the rupture. In the second instance, on the other hand, the portions first touched are contracted before the other parts have had time to cool, and rupture is again the consequence of this sudden molecular movement. We all know that boiling water cannot be poured into a cold glass vessel without breaking it by the quick expansion of the sides in contact with the liquid.

During hot summers the expansion of metals used in buildings and their contraction by cold in winter, produce effects which are the more apparent when these metals are united to materials whose expansibility differs from their own. The following is a curious example, quoted by Tyndall in his work on Heat, the observation and explanation of which is due to Canon Moseley:—"The choir of Bristol Cathedral was covered with sheet lead, the length of the covering being sixty feet, and its depth nineteen feet four inches. It had been laid on in the year 1851, and two years afterwards it had moved bodily down for a distance of eighteen inches. The descent had been continually going on from the time the lead had been laid down, and an attempt to stop it by driving nails into the rafters had failed; for the force with which the lead descended was sufficient to draw out the nails. The roof was not a steep one, and the lead would have rested on it for ever, without *sliding* down by gravity. What then was the cause of the descent? Simply this. The lead was exposed to the varying temperatures of day and night. During the day the heat imparted to it caused it to expand. Had it lain upon a horizontal surface, it would have expanded all round; but as it lay upon an inclined surface, it expanded more freely downwards than upwards. When, on the contrary, the lead contracted at night, its upper edge was drawn more easily downwards than its lower edge upwards. Its motion was therefore exactly that of a common earthworm: it pushed its lower edge forward during the day, and drew its upper edge after it during the night, and thus by degrees it crawled through a space of eighteen inches in two years."

From this example we learn how important it is to note the changes of volume in solids which are used in building or the arts. Railway lines lengthen in summer and shorten in winter; it is necessary, therefore, on laying them, to give them a certain play which allows the lengthening to take place freely, otherwise the heat would force the bolts from the sleepers, or would contort the line. The damaged line which occasioned the Fampoux accident on the Northern Railway of France was apparently caused by a contortion of this nature, as the ends of the rails had not a sufficient interval between them.

Stones held together by iron clamps are often broken, either by the expansion or contraction of the metals, both being greater than that of the stone. The force with which the molecules of bodies are sometimes separated and sometimes drawn together, one against the other, by change of temperature, is enormous. A bar of iron a metre (39·3 inches) long expands lengthways 1·17m., when its temperature is raised from 0° to 100°; it contracts to the same amount in passing from 100° to 0°. Now, it has been calculated that in order to overcome this molecular movement, a force equal to the pressure of 2,450 kilogrammes must be employed, if the section of a bar of iron is a square centimetre, and 245,000 kilogrammes if the section is a square decimetre. This force has been employed for the holding together of the lateral walls of a gallery in the Conservatoire des Arts et Métiers, which the pressure of the roof had driven out of the vertical. Two bars of iron were placed so as to cross the two walls at the upper part; they were terminated on the outside by screws furnished with nuts. The whole of their length was quickly heated, which produced a lengthening, and the nuts were then screwed up close against thick pieces of wood placed on the outside of the roof walls whilst the bars were still hot. On cooling, the bars contracted, and by degrees the force of contraction drew the walls nearer together. By repeating the same operation several times they were at last brought to a vertical position.

FIG. 291.—Room of the Conservatoire des Arts et Métiers. Walls rectified by force of contraction.

Cartwrights utilize the contracting force of cooling iron to bind together the spokes of carriage wheels. The iron tire is forged in such a way as to surround the wood, when it is heated to rather a high temperature; on cooling it binds the parts of the wheel strongly together.

Dutch tears, or Rupert's drops, are drops of melted glass which have been suddenly solidified in cold water. On breaking the filament of glass with which they are terminated, the whole mass instantly becomes powder, with such a force that if the drop has been previously plunged into a flask filled with water the shock transmitted to the water is sufficient to break the flask. A similar effect is produced in very thick glass flasks which have been cooled suddenly after having been blown. A grain of sand thrown into the vessel is sufficient to cause the bottom to fall out (Tyndall). The cause of this is the same in this last example as in the Dutch tears. The exterior of the glass drops cools first, imprisoning the interior mass, which has not yet solidified; when this cools in its turn, it contracts, and the effect of the contraction being exercised equally on the outer envelope, it remains in equilibrium. But the molecules are in a state of violent tension, and the least rupture suddenly destroys the equilibrium in one point, and at the same time destroys it in the whole mass.

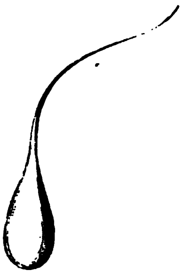

FIG. 292.—Dutch tears.

The expansion of liquids is generally greater than that of solids, and the expansion of gases is the greatest of all. We have seen how this is proved; it now remains for us to show by what means the expansions are measured, by what methods the so-called *co-efficient of expansion* of a solid, liquid, or gas is determined. The unit of volume of the body being given, let us imagine that the temperature is raised one degree centigrade: expansion or increase of volume will of course result. This increase, expressed in numbers referred to this same unit, constitutes the co-efficient of expansion of the substance for the temperature employed. In a more general sense, we may say that it is the fraction of the primitive volume added to the volume of any body when its temperature is raised one degree. Thus a litre or cubic decimetre of mercury heated from 0° to 1° becomes a litre *plus* 179 millionths, or 1·000179 decimetre.

The fraction 0·000179 is the co-efficient of expansion of mercury at zero. The numbers of which we here speak vary with the nature and physical condition of the substances. Moreover, the co-efficient of expansion of one body generally varies for different degrees of the thermometric scale, even when its physical condition does not change.

In liquids and gases the cubic expansion, or expansion of volume, is considered; but in solids it is possible to determine the increase of one of the dimensions, that is to say, the linear expansion, or, in the case of two dimensions, superficial expansion. As a solid of any form generally expands equally in every direction, so as to retain its original form at all temperatures, the increase of its volume can be deduced from that of one of its dimensions; besides, it is proved that the co-efficient of cubic expansion is perceptibly to all intents and purposes triple of the co-efficient of linear expansion; for this reason, in the case of solid bodies, this last co-efficient is alone determined.

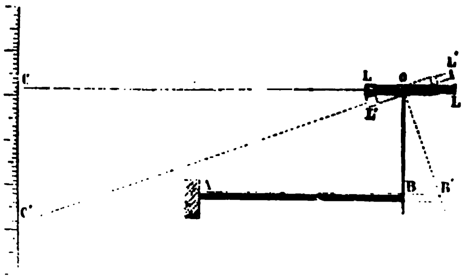

FIG. 293.—Measure of the linear expansion of a solid, by the method of Lavoisier and Laplace.

Let us now consider the nature of the method devised by Lavoisier and Laplace for measuring the linear expansion of a solid bar. The bar A B is fixed at A, so that it can expand only at the extremity B; on expanding through the space B B′ it forces the rod O B, which is fixed and can revolve on the point O, into the position O B′. The telescope L L, originally horizontal, moves with the rod to L′ L, so that, in place of being opposite the point C of the vertical scale C C′, it is then opposite C′. By this means they then substitute for the difficult measure of the smaller space B B′ that of a space C C′, the ratio of which to the space B B′, through which the rod has expanded, is equal to the ratio of O C to O B. Fig. 294 shows the arrangement of the apparatus employed in the preceding method. The metallic bar S, whose expansion is to be measured, is immersed in a trough filled with water, beneath which is placed a fire to raise the temperature; at one end it is in contact with a fixed glass rod B′, immoveably fixed to the pillars; at the other end it presses against the moveable glass rod B, which communicates its motion to the telescope. The water in the trough being first at 0°, the observers note the division of the scale with which the micrometric wire stretched horizontally across the field of the telescope corresponds. Then, after having replaced the iced water by water raised to a temperature of 100°—that is, to the boiling point—the division of the scale is again observed. By a simple proportion the relation of the elongation of the bar to its original length is determined; in other words, the expansion for 100° of temperature.

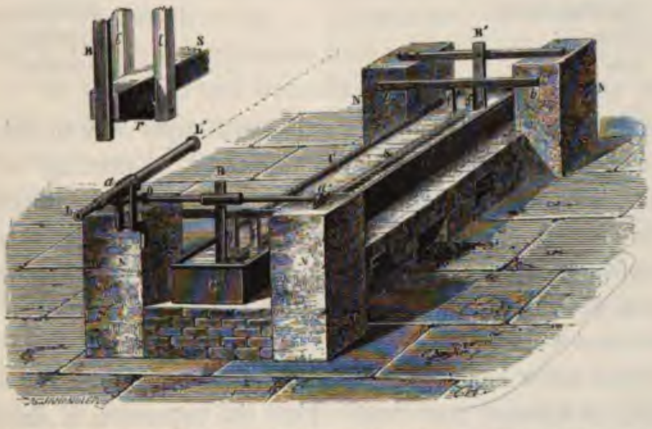

FIG. 294.—Laplace and Lavoisier's instrument for the measure of linear expansion.

Operating thus on solid bars of different substances and between different limits of temperature, Laplace and Lavoisier determined, for the co-efficients of expansion of solids, numbers which vary for different substances, but which are sensibly constant for the same substance for the different degrees of the thermometric scale, between the temperatures 0° and 100°. The following are some of the results determined by various observers either by the method just described or by other processes.

Iron	0·000012
Copper	0·000017
Tin	0·000022
Lead	0·000029
Zinc	0·000032
Silver	0·000019
Gold	0·000015
Platinum	0·000009
Steel	0·000011
Aluminium	0·000022
Bronze	0·000019
Wood Charcoal	0·000011
Granite	0·000009
White marble	0·000008
Building stone	0·000009
Glass	0·000008
Ice	0·000053

The preceding co-efficients of expansion apply only to the specimens which were used to determine them; according to some observers, the same substances are found to possess totally different co-efficients, dependent on the particular molecular conditions in which the substances used by each of them exist. Thus, wrought iron, iron wire, and cast iron have not the same co-efficient of expansion; and a similar remark applies to other metals. Solid bodies which have not a homogeneous structure in every direction expand unequally in different directions. Thus the expansion of dried wood is not the same in the direction of the fibres and perpendicular to their direction. All doubly-refracting crystals have unequal co-efficients of expansion in different directions. According to Mitscherlich and Fizeau, there are even some which, when they increase in length by heat in one direction, contract in another. Such is carbonate of lime or Iceland spar: for while, on raising the temperature one degree, this crystal expands 29 millionths in the direction of the optical axis, it contracts perpendicularly to the axis, and this contraction amounts to nearly 6 millionths. A similar phenomenon is observed in the emerald and in orthic feldspar. The differences of crystalline structure in different directions, which we have seen indicated in those substances by the curious effects of double refraction, are here shown under another form which is no less interesting.

Moreover, as we have just stated, these anomalies are not real exceptions to the law of expansion of solids by heat, because when the whole expansion is considered there is increase of volume. This is not the case however with iodide of silver. From some very interesting researches by M. Fizeau on this substance, it appears that it undergoes a real contraction in proportion as it increases in temperature between rather extensive limits, as they embrace 80 degrees of the thermometric scale; and further, that the co-efficient of contraction—which physicists call the *negative co-efficient of expansion*—becomes greater as the temperature increases.

For some time it was believed that ice or solidified water was contracted by an elevation of temperature, thus forming an exception to the general phenomena of expansion of solids: this however is not the case, and Brunner found that its density increased with the fall of temperature. The co-efficient of expansion of ice, as we have seen in the table at page 438, rises as high as 53 ten-millionths, higher, in fact, than that of zinc, the most expansible of all metals. Wood, and the greater number of organic substances, diminish in volume when they are warmed, if they are not completely desiccated; but this is only an apparent exception. Heat induces evaporation of the water which these bodies contain, and in diminishing in volume they also lose in weight; besides, on returning to their original temperature by cooling, they do not resume their primitive volume. Clay, although completely dried, also contracts when it is submitted to an increasing temperature, and it is on account of this property that clay pyrometers have been constructed; these instruments indicate the temperature of large kilns: but it has been proved that the contraction is owing to the commencement of vitrification or chemical combination of the elements of the clay; besides which, on cooling, it no longer assumes the former volume.

The expansion of liquids is greater than that of solids. We have already seen that the construction of ordinary thermometers is based on the difference of the expansion of glass and mercury. As the liquids, the expansion of which we desire to measure, are necessarily enclosed in solid vessels or envelopes, which themselves change in volume when the temperature is changed, it follows that we must distinguish between absolute expansion, that is to say, the real increase of volume of the liquid, and apparent expansion, as it is observed by the aid of a thermometric tube divided into parts of equal capacity. The absolute expansion of a liquid is evidently equal to its apparent expansion, *plus* the expansion of the envelope.

The following is the process employed for the measurement of the absolute or real expansion of liquids. The absolute expansion of mercury was first determined by a process which we cannot here describe; then, on subtracting from the number found the apparent expansion of the same liquid, the expansion of the glass was obtained. This being once known, the expansion of any liquid can be deduced from it by a reverse operation, that is to say, by first measuring the apparent expansion and adding to it the expansion of the glass or envelope.

Results have shown that liquids not only expand more than solids, but again that these co-efficients of expansion—this refers to cubic expansion—are not constant. Let us take some examples.

M. Regnault, by perfecting the method invented by Dulong and Petit, has obtained the following numbers, which represent the co-efficient of absolute expansion of mercury, for an elevation of one degree centigrade:—

	Co-efficients of cubic expansion of mercury.
Mean between 0° and 100°	0·00018170
at 100	0·00018305
at 200°	0·00018909
at 300°	0·00019413
at 350°	0·00019666

We perceive that the co-efficient increases with the temperature, but between 0° and 100° it is sensibly constant, and then equal to $\frac{1}{5500}$; while at 0° it is $\frac{1}{5585}$. Such is the fraction by which any volume of mercury expands at the temperature indicated.

Water and alcohol expand more than mercury between 0° and the temperatures 100° and 80°, which are their boiling points. Moreover, the first of these liquids offers an anomaly which deserves attention. Between the temperature of melting ice and 4°, water, instead of expanding, diminishes in volume; at this temperature it attains its maximum density. Heated above 4° it continues to expand till it reaches 100° C. M. Despretz, who has made a complete study of the expansion of water and its contraction near 0°, has given the following volumes and densities of water at different temperatures:—

Temperatures.	Volumes.	Densities.
0°	1·0001269	0·999873
1°	1·0000730	0·999927
2°	1·0000331	0·999966
3°	1·0000083	0·999999
4°	1·0000000	1·000000
5°	1·0000082	0·999999
6°	1·0000309	0·999969
7°	1·0000708	0·999929
8°	1·0001216	0·999878
100°	1·0431500	0·958634

The contraction of water heated from 0° to 4° can be proved very simply. A cylinder of glass, full of water at a temperature above 4° C., is surrounded, midway between the top and bottom, by a tray containing ice. The upper stratum of water gradually and continuously cools, and the thermometer which is immersed in it falls from 4° to 0°, whilst the lower thermometer, after having fallen to 4°, remains stationary. This experiment proves that the upper stratum on cooling to 4°, becoming heavier than the lower ones, falls to the bottom of the glass vessel, and is replaced by those, which are in turn cooled down by the ice. But when the temperature is lower than 4°, the water remains at the upper part, as the indications of the two thermometers prove.

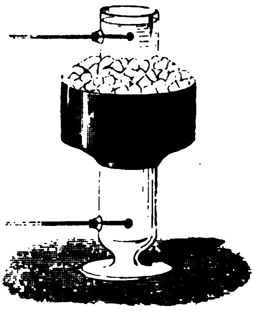
FIG. 295.—Experiment proving the contraction of water from 0° to 4°.

Gases expand much more than solids and liquids under the action of heat: a thin glass sphere, or a balloon of gold-beater's skin filled, with air, or any other gas, bursts when it is slightly heated. As according to Mariotte's law, the volume of a gas is changed by pressure, it is necessary, in order that its co-efficient of expansion may possess a definite value, that care be taken to indicate to what pressure it has been submitted. These co-efficients are ordinarily taken at an atmospheric pressure of 760 mm. Gay-Lussac determined a great number for temperatures comprised between 0° and 100°, and arrived at the remarkable result, that the co-efficient of expansion is the same for all gases, simple, mixed, or combined. According to this illustrious physicist, a volume of gas, on being heated 1° C., increases the 267th part of its volume: a cubic decimetre of air, passing from 0° to 100°, therefore expands 375 cubic centimetres, that is, more than a third of its volume at 0°. The number which we have just mentioned is a little too high, as the beautiful researches of M. Regnault have proved; and he has at the same time shown that Gay-Lussac's law is not absolute. Air, nitrogen, hydrogen, carbonic oxide have nearly the same co-efficient of expansion, which is 0·00366, which is equal to the fraction $\frac{1}{273}$. But those of other gases are different: thus, in the case of cyanogen, it is equal to 0·00388, or to the fraction $\frac{1}{258}$. Moreover, the less the pressure to which the different gases are submitted, the more do their co-efficients of expansion approach equality; thus verifying Gay-Lussac's law.

We shall see hereafter that the expansion of air and gases by heat explains many meteorological phenomena. It is also the principle of numerous applications, among which we may quote air balloons, hot-air stoves, and hot-air engines.

CHAPTER III.

EFFECTS OF VARIATIONS OF TEMPERATURE: CHANGES IN THE STATE OF BODIES.

The passage of bodies from a solid to a liquid state: fusion—Return of liquids to the solid state: solidification or congelation—Equality of the temperatures of fusion and solidification—Passage of liquids into gases: difference between evaporation and vaporization—Phenomenon of ebullition: fixed temperature of the boiling point of a liquid under a given pressure—Return of vapours and gases into a liquid condition: liquefaction and congelation of carbonic acid and several other gases—A permanent gas defined.

WE all know that a mass of water which is liquid at certain temperatures is capable of passing into the solid state when its temperature falls below a certain limit; in a word, it becomes a piece of ice without changing its nature, that is to say, without ceasing to be formed of the same chemical elements. On returning to its original temperature, it again resumes the liquid condition; and if it is then heated to 100°, under an atmospheric pressure of 760 mm., it is converted into vapour. The greater number of liquids are like water in this respect, and can exist in either the solid, liquid, or gaseous condition.

Bodies which are solid at ordinary temperatures, metals for example, change their condition when they are submitted to a sufficiently intense heat; they are then liquefied, and sometimes vaporized. Cooling produces opposite phenomena, and causes a gas to pass into a liquid, and then into a solid.

These various changes of condition are effected under circumstances which vary with the nature of the substance, but which nevertheless conform to certain common laws, which we shall now discuss. First, however, let us enumerate the changes of condition in solids, liquids, and gases, which can be produced under the influence of variations of temperature.

An increase of temperature produces, in solids, a change to a liquid state, which is called *fusion;* in liquids, it gives rise to a gaseous state, or *vaporization:* we shall see, further on, the distinction which must be made between vaporization and *evaporation,* which also designates the change of a liquid into gas, or into vapour.

Cooling causes gases to become liquid: this is *liquefaction;* and in liquids, a return to the solid state, which is sometimes called *solidification,* and sometimes *congelation* or freezing.

The fusion of different solid bodies takes place at various temperatures, which differ from each other considerably. Thus, whilst ice melts at 0°, sulphur at 125°, and lead at 322°, a temperature of 1,500° is necessary to melt iron, and nearly 2,000° to melt platinum. But all solids have this common property, that the temperature of fusion is definite for each of them; moreover, during the time that the change from the solid to the liquid condition is taking place, the temperature of the mass remains the same, whatever may be the intensity of the heat which produces the fusion. We may remember that it is this property which has been utilized in determining a fixed point of the thermometer. The only effect which is produced by an increase in the source of heat, is a greater rapidity in the fusion of the solid.

The passage to a liquid state of the greater number of solids is made suddenly; thus, ice, sulphur, and metals assume their fluidity in a moment. Other substances, on the contrary, begin by being softened; and they become viscous, before becoming quite fluid. Glass affords an example of this condition, which gives great facility to the working of it, and enables it to be blown and to be worked into various forms.

Formerly we were not able to produce a temperature sufficiently high for the fusion of certain bodies: hence they were called refractory or fixed. In the present day the number of these substances is considerably diminished, and the fusion of rocks, which used to be considered infusible, has been effected. M. Despretz has even succeeded in producing an incipient fusion in charcoal, the most refractory of all known bodies. Other solids are infusible, because heat decomposes them; such are chalk, pit-coal, and marble: nevertheless, by enclosing a piece of marble in an iron cylinder, hermetically closed, and then submitting it to a high temperature, a certain portion of this body can be fused. The heat at first decomposes part of the marble into carbonic acid and lime, and the gas, by its elastic force, prevents the continuance of decomposition, and the remaining marble is partially fused.

The expansion which a solid body undergoes when submitted to increments of heat, generally continues until the commencement of fusion; at this juncture it takes place still more rapidly, so that the liquefied mass has a greater volume than that of the solid which produced it. There are some exceptions to this law, and we shall have occasion to return to this subject in speaking of the solidification of liquids. A foreseen relationship exists between the latter phenomenon and that which we have just studied: for they are both effected for the same substance, at a fixed temperature: in a word, the point of solidification is the same as the point of fusion. Thus, water becomes ice when its temperature reaches 0°; lead is solidified when cooled to 322°, sulphur to 115°, iron to 1,500°, platinum to 2,000°. And we have another similarity in the fact that the temperature of the liquid mass remains constant during the whole time of solidification; a more intense removal of heat renders the passage to the solid state more rapid, but it does not lower the temperature of the mass.

The term *congelation* or freezing is more particularly applied to solidification which takes place at a low temperature,—for example, below 0°. Water congeals at 0°, mercury 39° below 0°; many liquids, such as bisulphide of carbon and alcohol, have not yet been solidified, although by using refrigerating mixtures their temperature has been lowered to 80° below 0°.

We thus see that the temperature of the fusing point of solids is the same as the temperature of solidification. Nevertheless it is possible, under certain circumstances, to lower the temperature of a liquid mass below this point without producing solidification. Water, for example, when enclosed in a vessel and sheltered from the agitation of the air, can remain liquid at a temperature 20° below 0°. In this experiment it must be very limpid, in order that it may be kept at perfect rest, and that the cooling be effected gradually. But when it is in this condition, the slightest agitation, or the throwing in of a small piece of ice, is sufficient to cause congelation to take place instantly throughout the whole mass. Then a remarkable result occurs, for there is a disengagement of heat, and freezing takes place at a temperature of 0°, as under ordinary circumstances.

A solid, on melting, expands quickly, and the reverse phenomenon ought to take place when a liquid mass is solidified. Experiment, indeed, has shown that there is a diminution of volume. But this is not a general law, as there are exceptions, such as water, cast-iron, bismuth, and antimony. These substances expand on solidifying, and this property is utilized in the arts, in the case of molten iron, and allows the reproduction in a very perfect form of the interior of the moulds in which this substance flows.

We have already learnt that water expands on cooling from 4° to 0°, so that the sudden expansion which it undergoes on congealing appears to be the continuation of the same phenomenon, and renders the explanation which is given to it probable: the phenomenon is explained by the new disposition which the molecules take in the vicinity of the point where this crystallization is effected. When the passage to the solid state is effected, the expansion is sudden, and is performed with an irresistible force, as shown by the following experiment, the description of which we take from Tyndall's "Treatise on Heat:"—"But to give you an example of this energy, a quantity of water is confined in this iron bottle. The iron is fully half an inch thick, and the quantity of water is small, although sufficient to fill the bottle. The bottle is closed by a screw firmly fixed in its neck. Here is a second bottle of the same kind, prepared in a similar manner. I place both of them in this copper vessel, and surround them with a freezing mixture. They cool gradually, the water within approaches its point of maximum density; no doubt at this moment the water does not quite fill the bottle, a small vacuous space exists within. But soon the contraction ceases, and expansion sets in; the vacuous place is slowly filled, the water gradually changes from liquid to solid; in doing so it requires more room, which the rigid iron refuses to grant. But its rigidity is powerless in the presence of the atomic forces. These atoms are giants in disguise, and the sound you now hear indicates that the bottle is shivered by the crystallizing molecules,—the other bottle follows, and here are the fragments of the vessels, showing their thickness, and impressing you with the might of that energy by which they have been thus riven."

Two bombs filled with water, the fusee holes being closed firmly by an iron stopper, were exposed to intense frost: in one instance the stopper was projected to a distance of 150 metres on freezing, and a long cylinder of ice issued from the opening (Fig. 296); the other bomb was split open, and a sheet of ice was forced through the crack. This experiment is given in M. Daguin's "Traité de Physique," and was made by Major Edward Williams, of the Artillery in Quebec.

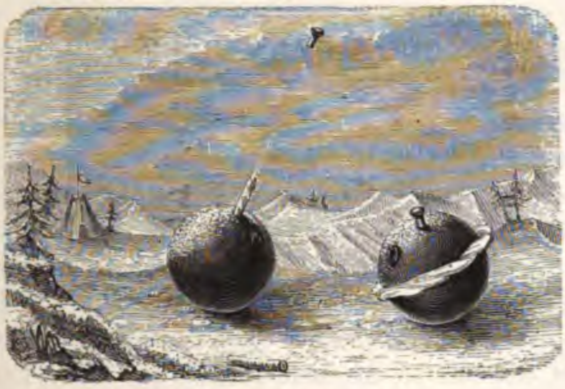

Fig. 296.—Effects of expansion produced by the freezing of water.

Similar results have been obtained with bismuth. An iron bottle filled with melted metal, and closed with a screw-stopper, bursts when the metal begins to solidify; the rapid expansion which determines the changes of condition develops an expansive force so considerable that the envelope cannot resist it, and is broken.

The expansion of water at the moment of congelation explains the bursting of water-pipes during a frost; the accident is not perceived until a thaw, because as long as the water remains as ice in the pipes no escape can be manifested, but when the thaw commences, the water flows through the cracks in the pipes.

The greater number of solids must be liquefied before they pass into the state of vapour. Nevertheless, camphor, arsenic, and some other substances diminish in weight when exposed to the air, without becoming liquid. Snow and ice do the same. Everyone can observe this fact during dry weather and hard frosts: pieces of ice and heaps of snow perceptibly diminish in volume, or quite disappear, without even partial fusion having taken place.

As regards liquids, they for the most part pass spontaneously into vapour, at varying temperatures. Water on being placed in an open vessel gradually disappears; wet things dry with much greater rapidity when the temperature is high and the surrounding air not humid; and again, when placed in a current of air, the water with which they are saturated is converted still more quickly into vapour. Mercury evaporates at ordinary temperatures; a fact which was placed beyond doubt by Faraday, by means of the following experiment: he suspended a piece of gold leaf in a flask containing mercury, and after some length of time he found that the leaf was whitened. The mercury had thus amalgamated itself with the gold, which could not have resulted unless evaporation had taken place. This first mode by which liquids pass into the state of gas is called *evaporation*. It is characterized by the fact that it is effected at any temperature whatever, and solely at the superficial stratum of the liquid. *Vaporization*, on the other hand, is the conversion into vapour under the influence of a rise of temperature at the moment when this temperature attains a fixed limit, determinate for each liquid, and constant for the same external pressure. The liquid is then in ebullition, that is to say, its mass is agitated by the passage of the bubbles of vapour which have escaped from the bottom of the vessel which contains it, and the specific lightness of which causes them to ascend to the surface.

The temperature at which a liquid enters into ebullition is, as we have just said, constant for the same pressure: that is, if the liquid is always contained in a vessel of the same substance. Water boils at 100°, at the barometric pressure of 760 millimetres, in a metallic vessel; in a glass vessel, however, it scarcely boils at 101°, as proved by Gay-Lussac: this probably proceeds from a stronger adhesion of the liquid molecules to the glass than to the metal. Moreover, the temperature of ebullition remains constant during the whole time that the vaporization of a liquid mass continues; only, if a more intense heat is used, the passage into the vaporous state is effected more rapidly.

The following are the temperatures at which vaporization (which always accompanies ebullition) takes place in the case of the following liquids:—

Ether	35°
Alcohol	80°
Water	100°
Concentrated sulphuric acid	325°
Mercury	350°
Sulphur	400°

Let us now study more closely the curious phenomena of the ebullition or boiling of liquids, and we will take for our example that liquid which is most easy to observe, viz. water.

When the temperature of a vessel containing water is raised by placing it on the fire, the bottom and sides of the vessel receive the first influence of the heat. The heat is then communicated to the contained liquid, which is at first evaporated at the surface, this evaporation being greater as the temperature of the water approaches nearer to ebullition. At length the moment arrives when vapour is produced on the inner surfaces and at the bottom of the vessel. The bubbles there formed have an elastic or expansive force, which, added to their specific lightness, causes them to rise to the surface of the liquid. But the weight of the strata of water and the atmospheric pressure are opposed to this ascent, which does not effectively take place until the elastic force of the vapour is equal to the sum of these two pressures. Then a tumultuous movement commences, which is due to the passage of bubbles which burst at the surface of the liquid. A little before ebullition, a peculiar noise is heard: it is then said that the *water sings.* The production of this noise may be explained as follows: when the first bubbles of vapour rise to the surface, they traverse strata more or less warm, the vapour of which they are formed is cooled and condensed, and the surrounding water immediately fills the spaces

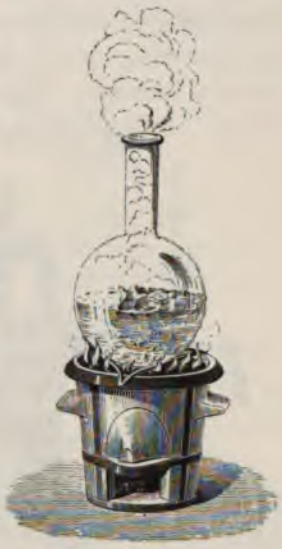

FIG. 297.—Ebullition in open air.

which result. But the upper strata of the water soon attain the temperature of the strata at the bottom, and the noise ceases, because the cause of the condensation of the bubbles has disappeared.

The appearance of the bubbles of vapour confirms this explanation; they at first rise under the form of cones which taper off at the upper part; when ebullition is complete they rise, on the contrary, as cones widened at the top, because, instead of being condensed, they are expanded in proportion as they overcome the diminishing pressure of the liquid above them.

Experiment proves that, during the whole time of boiling of a liquid, the elastic tension of the vapour which is formed is precisely equal to the external pressure; and, because, as we shall presently see, this tension increases with the temperature, it follows that the temperature of ebullition of a liquid is lowered as the external pressure decreases, and, on the contrary, that it is raised as the external pressure increases. Thus, under a pressure of 760 mm. water boils at 100°. De Saussure, having boiled water on Mont Blanc, found 86° to be the temperature of ebullition, the barometric pressure being 434 mm.; Bravais and Martins made similar experiments, and found the temperature of ebullition at the Grands-Mulets, on the sides of the same mountain, 90°, under a pressure of 529 mm., and at the top of Mont Blanc 84·4°, with a pressure of 424 mm.

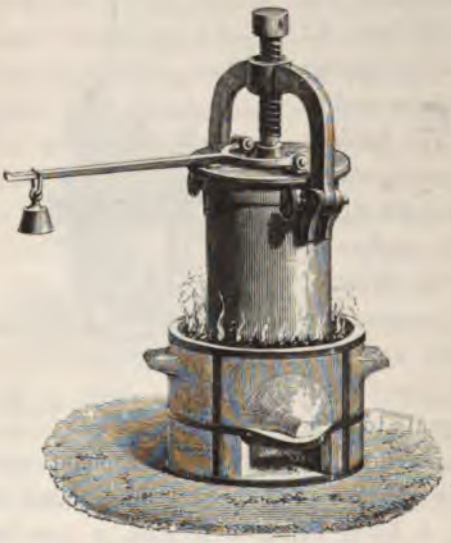

FIG. 298.—Papin's Digester.

In an apparatus called (after its inventor) Papin's Digester, the temperature of ebullition of water is raised at will, by increasing the pressure on the surface of the liquid. The increased pressure is produced by the vapour, which accumulates in large quantity above the surface, and raises the boiling point of the liquid. Papin's

Digester is composed of a cylindrical vessel made of iron or bronze, with thick and excessively strong sides; it is closed by a cover of the same metal, which a pressure-screw presses against the edges of the opening (Fig. 298). A hole in the cover allows the vapour to escape, whenever its tension exceeds a certain limit, which can be fixed at pleasure by the following means: the hole in the cover is closed by the arm of a lever, at the extremity of which is a weight acting with a force proportional to its mass and the length of the arm of the lever.

The limit of the elastic force of this vapour, or, in other words, that of the temperature of the water contained in the vessel, can thus be regulated beforehand. Water can thus be boiled at a constant temperature far exceeding 100°, a temperature capable indeed of melting tin, bismuth, and lead. Papin's Digester is used to dissolve or boil in water substances which require a higher temperature than that of ebullition in free air, at the ordinary pressure of the atmosphere.

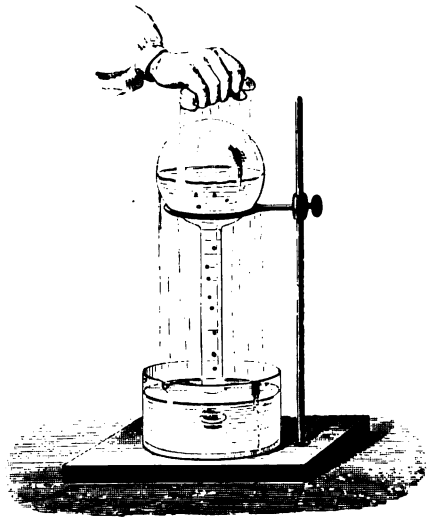

FIG. 299.—Ebullition of water at a temperature lower than 100°.

We have mentioned that the ebullition of liquids takes place at temperatures which are lower as the pressure decreases; now, on placing under the receiver of an air-pump a vessel containing water at a temperature below 100°, this liquid is seen to enter into ebullition as soon as, on rarefying the air, the pressure falls to that of the elastic force of steam at this temperature; the vapour thus formed accumulates above the surface of the liquid, and by its increasing pressure ultimately stops the ebullition. If the receiver is now cooled by means of a wet cloth, the fall of temperature condenses a part of the vapour, and thus diminishes the pressure, and ebullition recommences.

This experiment can be tried without the aid of an air-pump.

tained in a bulb with a long neck, is submitted to a ebullition, in order that the air may be completely ex- ie vapour which is formed; the flask is then corked and m the fire, and in order to prevent the entrance of air, the mersed in water (Fig. 299). The vapour which remains liquid has a tension sufficient to prevent ebullition; but is cooled by pouring cold water over it, or by putting it in contact with ice, the vapour is condensed and ebullition recommences: it seems as if water is boiled by being cooled.

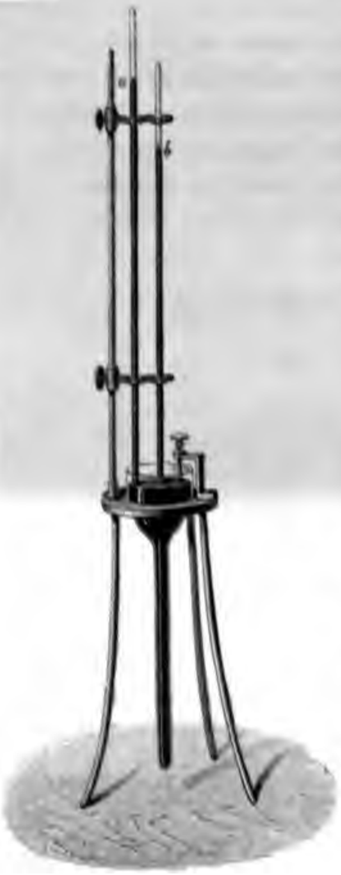

FIG. 300.—Spontaneous evaporation of a liquid in the barometric vacuum. First law of Dalton.

To understand thoroughly the conditions under which the last change of state—the *liquefaction of gases*—which remains to be studied takes place, it is indispensable for us to know the laws which regulate the formation of vapours *in vacuo*, the experimental demonstration of which is due to the physicist Dalton. The following is an account of them:—

If we introduce into the Torricellian vacuum a certain volume of any liquid, for instance, a cubic centimetre of alcohol, the level of the mercury is seen to be depressed, and to stop at a point *b* (Fig. 300); and its distance from the level of a barometer, immersed in the same basin as the first tube, measures the tension or elastic force of the vapour formed. We see at once that *in vacuo* liquids pass spontaneously into vapour.

Let us suppose that a thin stratum of liquid is floating on the mercury: if the tube is now raised without lifting the lower end out of the mercury, the level will be observed to remain at *b*, that is to say, at the same height as before. But the liquid stratum of alcohol diminishes in thickness in proportion as the space occupied by the vapour increases; a fresh quantity of vapour is formed without a change of tension; and thus it continues until the whole of the liquid is evaporated. If we now continue to raise the tube, that is, to increase the space which the vapour occupies, the level of the mercury will rise, which proves that the tension of the vapour diminishes. The tube being again lowered, the level falls and comes back to the point *b;* but if then the same movement be continued, the level remains constant, while an increasing portion of the vapour resumes the liquid form. Figure 301 represents three barometric tubes, the chambers of which are filled with the vapour of the same liquid; as long as this remains in contact with the liquid itself, its tension does not vary, which is proved by the equal height of the mercury in the three experimental tubes.

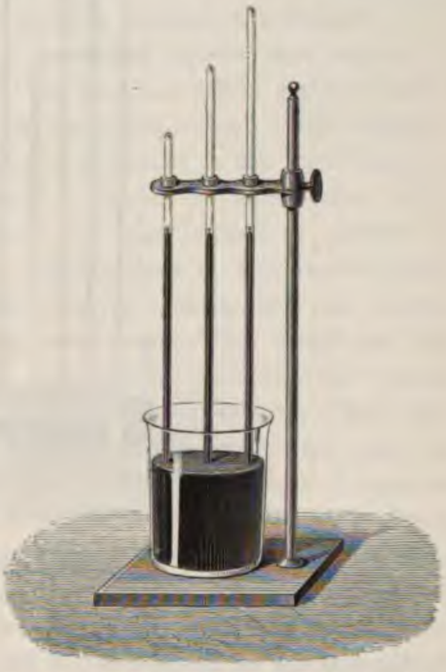

FIG. 301.—Invariability of the maximum tension of the same vapour at the same temperature. Dalton's second law.

From this first experiment Dalton concluded:

1st. That a liquid placed in a vacuum vaporizes spontaneously.

2nd. That the vapour thus formed attains a maximum degree of tension which remains invariable whilst an excess of liquid remains in contact with the space filled with vapour. It is then said that the space is *saturated* with vapour.

If we make the experiment with liquids of various kinds—water, alcohol, ether, &c.—we find that the maximum tension varies with different liquids at the same temperature; this is proved by the different levels of the mercury in the barometer tubes shown in

Figure 302. If the temperatures are caused to vary, these phenomena are produced in the same order, but the maximum tension increases rapidly. The following table gives the tensions of aqueous vapour in a vacuum, at different temperatures, expressed either by the number of millimetres of mercury which it supports in a barometric tube, or by the number of atmospheres of 760 millimetres.

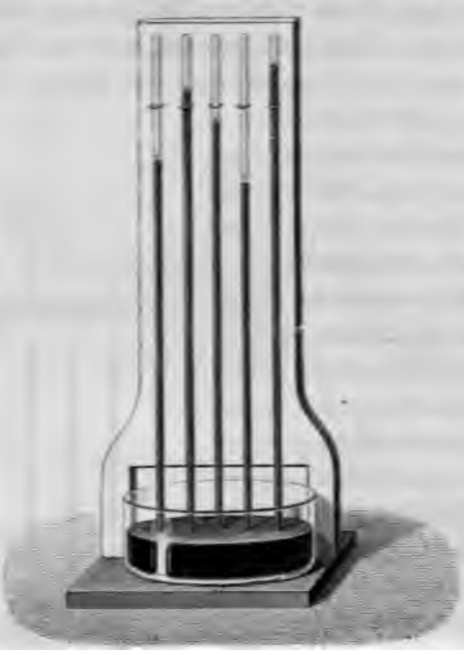

FIG. 302.—Inequalities of the maximum tensions of different vapours at the same temperature. Dalton's third law.

Temperatures	Tensions. mm.	Temperatures.	Tensions.
— 10°	2·1	+ 120°	2 atmospheres.
0°	4·6	+ 134°	3 „
+ 10°	9·2	+ 144°	4 „
+ 20°	17·4	+ 152°	5 „
+ 30°	31·5	+ 180°	10 „
+ 40°	55·0	+ 212°	20 „
+ 50°	92·0	+ 252°	40 „
+ 100°	760·0	+ 266°	50 „

By this table it is seen that at the ordinary temperatures, between 10° and 30° for instance, the maximum tension of aqueous vapour *in vacuo* does not exceed 32 millimetres. A pressure higher than 32 millimetres, at the temperature of 30°, will cause a part of the vapour to return to the liquid state. Nevertheless, we see water spontaneously vaporized in the open air, under a much greater pressure, the mean being 760 mm. This is an apparent anomaly, which proves the tendency which gases possess to rise by virtue of the expansive force which belongs to them; the air truly presses on the surface of the water, but as air is a porous body, its molecules having spaces between them, the molecules of aqueous vapour fill these intervals, and thus mix with the gas of which the atmosphere is formed.

The laws of the mixture of gases and vapours were studied by Gay-Lussac, who demonstrated that, if a space full of gas is saturated with the vapour of any liquid, the maximum tension of this vapour is precisely that which it possesses in a vacuum at the same temperature. The more the temperature is raised, the more vapour will a space, whether vacuous or filled with gas, require to saturate it. Thus in summer, in very warm weather, there is often more aqueous vapour in the air than in winter, during a damp and cold season. This fact astonishes many people who consider that clouds and fogs are formed of aqueous vapour; but this is a mistake, for aqueous vapour is always perfectly invisible and transparent. The very minute drops of which fogs and clouds are formed are water in the state of liquid, not of vapour; in other words, it is aqueous vapour which the lowness of the temperature has condensed. There are, it is true, substances whose vapours are visible—for example, iodine; but this results from the fact that this vapour is not colourless like that of water, for it is of a beautiful purple-violet. Again, the vapour of chlorine is visible, on account of its greenish-yellow colour, that of bromine by its brownish-red colour.

When a gas or vapour is contained in a closed space, its liquefaction can be produced by two methods—viz. either by lowering its temperature or diminishing its volume. But, in order that the liquid may appear, it is necessary that the space be previously saturated; and it is also by this same means of cooling or compression that the state of saturation is obtained. By vapour is understood the condition of a substance which was before in a liquid state. There is no difficulty in liquefying any vapour, if we place it under the conditions of temperature and pressure which it possessed when it existed in the liquid state.

The liquefaction of gases presented many difficulties which by degrees have been obviated. Ammonia gas, chlorine, carbonic acid gas, and protoxide of nitrogen have been liquefied—and even, with the exception of chlorine, solidified—thanks to the use of vigorous processes of compression and refrigeration. Five gases now alone remain which have not been liquefied by any known means; these are, hydrogen, oxygen, nitrogen, carbonic oxide, and binoxide of nitrogen—a temperature of 110° below zero, combined with a pressure of from 30 to 50 atmospheres, has left them still in the gaseous state: for this reason they are called *permanent gases.* But induction authorizes us to believe that it would be possible to reduce them, like other gases, to the liquid state by using more powerful means, for in a recent research Dr. Andrews of Belfast has shown it to be probable that the various states of matter are continuous, the liquid state forming a link between the solid and gaseous states—a link however at times suppressed when the solid passes at once into the gaseous or vaporous form—and he holds that the gaseous and liquid states are only distant stages of the same condition of matter, and are capable of passing into one another by a process of continuous change.

CHAPTER IV.

PROPAGATION OF HEAT.—RADIANT HEAT.

Heat is transmitted in two different ways, by conduction and by radiation—Examples of these two modes of propagation—Radiation of obscure heat *in vacuo*—Radiant heat is propagated in a straight line; its velocity is the same as that of light—Laws of the reflection of heat; experiments with conjugate mirrors—Apparent radiation of cold—Burning mirrors—Refraction of heat; burning glasses—Similarity of radiant heat and of light—Study of radiators, reflectors, absorbing and diathermanous bodies—Thermo-electric pile; experiments of Leslie and Melloni.

WHILE describing the effects of heat on matter, effects which modify its volume, or change its physical condition, we have said nothing of the manner in which the passage of heat from the heat-source to the heated body is effected. When two bodies are in the presence of each other, either in contact or at some distance apart, experiment proves that an interchange of heat takes place between them, how little soever their temperatures may differ; so that each of them becomes a source of heat to the other: but we, more often, reserve the term heat-source for that of the two bodies which possesses the higher temperature. We shall now study the different modes of transmission of heat when it passes from a heat-source to a body which is more or less distant, or is transmitted through various media.

Experiment has shown us two principal modes of propagation of heat, and we observe that the following examples may be easily multiplied by adding our daily observations of like phenomena. When a cold iron bar is held in the hand by one of its extremities, the other end being placed in the fire, a certain time elapses before the heat of the fire, which is gradually transmitted along the bar, is perceptible to the touch; the shorter the bar, the less time does the heat take to travel along it; moreover, the intensity of the heat thus propagated increases from the moment of the first impression, if the bar still remains in the fire. Here, the heat has travelled along the metal, and from molecule to molecule; it is by the intervention of material particles that it has thus been conducted from one extremity to the other of the iron bar, and lastly communicated to the hand by contact. This is an example of the propagation of heat by conduction. It is in this way that the temperature of the exterior walls of a vessel is raised, when hot water has been poured into the interior. The same mode of transmission does not obtain, however, when the heat of the fire is communicated to the face of a person who removes a fire-screen quickly from before him, and thus becomes exposed to its influence. In this case the rapidity of the impression proves that it is not by warm air interposed between the fire and the face that the heat of the fire has been propagated, but by a movement analogous to that of light emanating from a luminous source. The heat is then said to be propagated by *radiation*, and *radiant heat* is that which is emitted from a source of heat and thus transmitted to a distance.

Thus, when a source of heat is in the presence of, and at a certain distance from, a body, it can raise its temperature in two ways: either by gradually warming, molecule by molecule, all the material parts which are interposed between the body and the source, or by warming the body directly, without an elevation of temperature of the intermediate parts being a necessary condition to the elevation of the temperature of the body. Heat is propagated by *conduction* in the first instance, by *radiation* in the second.

As all other methods of transmission of heat may be included in one or other of these, or by their combination, we shall study them separately, and we will commence with radiant heat.

The action of the solar rays, which make themselves felt at a distance of 91 millions of miles, proves that heat does not require a medium of a ponderable nature for its propagation; and, indeed, when, after having traversed the interplanetary spaces, it enters the atmosphere, and ultimately reaches the earth, it warms this latter directly, without having raised to a perceptible degree the temperature of the upper strata of the atmosphere, to which the cold which exists in high regions of the air, on the summit of lofty mountains, testifies.

Heat radiates from all the incandescent bodies which may be observed on the face of the earth, in the same way as it emanates from the sun. Obscure heat also possesses the same property, that is to say, it is propagated from its source to any distance by direct radiation, without warming the intermediate space, as during conduction. Rumford's experiment has placed this result beyond doubt. He constructed a barometer, the tube of which was terminated at its upper extremity by a large bulb, in the centre of which a thermometer was placed; the bulb thus formed the vacuous chamber of the instrument, so that it was entirely void of ponderable matter (Fig. 303). Having then closed the orifice of the stem, and sealed off the bulb from it, he plunged the lower part of this latter into boiling water; the mercury in the thermometer rose *immediately*—an effect which could be attributed only to the radiation across the vacuum of the heat communicated by the water to the mercury in the bulb.

FIG. 303.—Radiation of obscure heat *in vacuo.*

Thus obscure heat radiates from calorific sources in the same manner as luminous heat.

We will now show a more complete analogy between the phenomena of radiant heat and light; the same laws regulate both, so that luminous and calorific effects appear to be produced by movements of the same nature, for we are already aware of the existence of heat-rays beyond the red end of the solar spectrum.

Like light, radiant heat is transmitted in straight lines through homogeneous media; if therefore we interpose, between a source of heat and one of the bulbs of Leslie's differential thermometer, a series of screens, each pierced with a hole, the instrument will mark the elevation of temperature only so long as the holes of the screens remain in a straight line. This experiment proves that bodies exist of such a nature that radiant heat does not pass through them: they are called *adiathermanous* substances. Other substances which are traversed with more or less facility by heat-rays are called *diathermanous:* these latter are generally transparent substances, such as air and other gases; but there are also opaque bodies which permit the passage of radiant heat, and are hence diathermanous.

The velocity of propagation of radiant heat is as great as the velocity of light. The first series of experiments proved that there is no appreciable interval between the moment when a screen, interposed between a source of heat and a very sensitive thermoscope, is removed, and that in which the instrument marks the elevation of temperature. Mariotte worked thus at a distance of more than 100 metres: Pictet at 23 metres. But these experiments only prove that the velocity of radiant heat is great, without giving its measure; it has since been proved that there is a perceptible difference between the velocity of the dark heat-rays of the solar spectrum and of light rays.

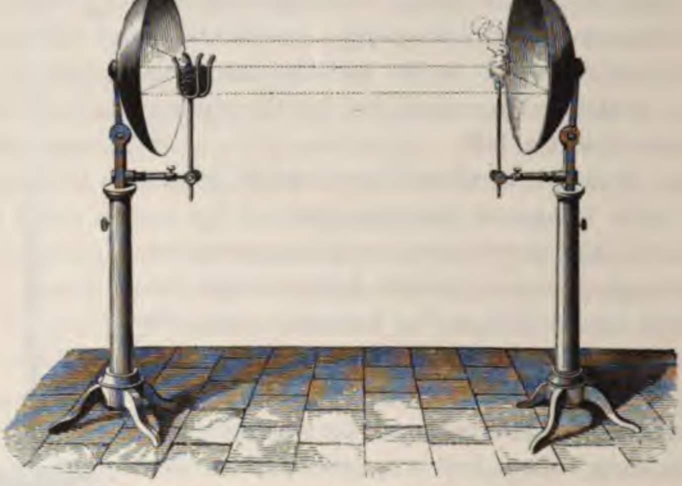

FIG. 304.—Reflection of heat; experiments with parabolic conjugate mirrors.

Radiant heat is reflected from the surface of bodies, like light, and in accordance with the same laws. We can assure ourselves of this identity, by showing that the effects of a radiating source are analogous to the luminous effects of reflection. Thus, if we place two parabolic mirrors opposite to each other, so that their axes coincide (Fig. 304), a source of heat placed in one of the foci will transmit, to the nearest mirror, rays which will be reflected parallel to the common axis, and after falling on the second mirror will, after this new reflection, be reunited in its focus. This is what ought to take place if the laws of the reflection of heat are the same as those of light; and we find that such is the case. In one of the foci we place an iron basket containing burning coals, and in the other focus some gunpowder, tinder, gun-cotton, or any other inflammable substance,—it takes fire instantly. This experiment will not succeed, if the source of heat or the inflammable body be displaced, however little, from their respective foci. An experiment of Sir H. Davy has proved that the laws of the reflection of radiant heat are the same *in vacuo* as in air. Moreover obscure heat is propagated like heat which radiates from incandescent sources, which may be demonstrated by the experiment of the conjugate mirrors by means of a vessel filled with boiling water. This vessel is placed in one of the foci and the bulb of a thermometer in the other, which immediately indicates a rise of temperature. The same thermometer placed away from the focus manifests no perceptible change.

We will now speak of a curious experiment which would lead us at first sight to believe that cold can be radiated as well as heat. If a piece of ice is substituted for one of the sources of heat, of which we have just spoken, and if it is placed exactly in the focus of one of the mirrors, the thermometer in the other focus falls, as if a reflection of cold had taken place. The fact in this case is, as in the others, that there are two bodies of unequal temperature in the presence of each other, both of which radiate heat. Each of them suffers a loss of heat, which is partly compensated for by the gain which follows from the radiation of the other. In the first experiment, the thermometer received more than it lost, and therefore there was an increase of temperature and an elevation of the mercurial level. In the ice experiment, the thermometer on the contrary loses more heat than it receives; its temperature diminishes, and the mercury sinks.

The laws of radiant heat have been utilized in obtaining a heat of very great intensity at the focus of a spherical concave mirror exposed to the solar rays. With an apparatus of this kind, which is then called a *burning mirror* (Fig. 305), and which possesses a large diameter and considerable curvature, metals have been melted, bricks and stones vitrified, &c. Buffon obtained this effect from spherical mirrors, by placing 100 silvered plane mirrors in such a manner that each of them was a tangent to the same sphere; each mirror turned on a hinge, and he thus increased or diminished the distance of the focus at will. By means of this mirror he melted lead at a distance of 140 feet (45·5 m.), and silver at 100 feet (22·5 m.).

The rays of heat which fall on a body are not all reflected. They are generally divided into two groups. The first group consists of the rays which are reflected from the surface of the body according, as we have just stated, to the laws of reflection of light: there are also other rays which are diffused in every direction; but none of these rays penetrates into the substance of the body. The second group is formed of the rays which are absorbed by this substance, and produce in it an elevation of temperature, being propagated by conduction throughout the whole mass: and, lastly, rays which pass through the body, and issue in the same manner as light traverses and issues from transparent media. The proportion of these different fractions of incident heat-rays varies according to the nature of the body which receives them, the state of its surface, &c. Hence the expressions, *reflecting, diffusive, absorbing,* and *diathermanous powers,* to designate the properties which correspond to these different modes of radiation of heat by various bodies. We shall speak of these hereafter. At present we will confine ourselves to the phenomena of the transmission of radiant heat through diathermanous media, and to the laws of its propagation, because we shall find an analogy between heat and light in this respect.

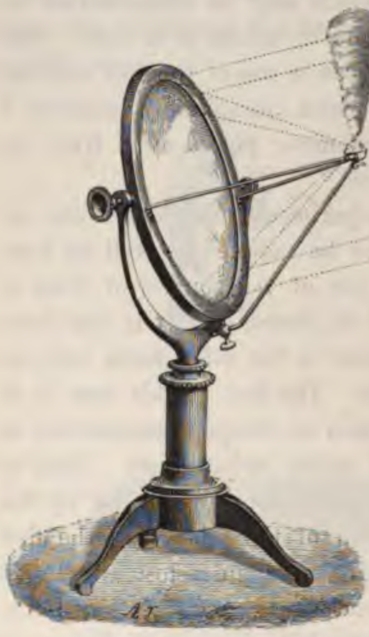

FIG. 305.—Burning mirror.

Heat-rays, when they enter a diathermanous medium, undergo the deviation which we have studied in light under the name of *refraction.* If the calorific beam falls perpendicularly on the surface of the medium, there is no deviation. But at another incidence the ray is deviated, and approaches the normal at the point of incidence, in passing from one medium to another of a greater density; in a word, the laws of refraction of heat have been demonstrated to be like those of the refraction of light. This fact has been proved experimentally by using convergent spherical lenses to concentrate the calorific rays which accompany the luminous rays of the sun. At the focus, where the light is most intense, the heat is also the greatest; and everyone can verify the truth of this fact, by setting fire, by the aid of a magnifying glass, to even a slightly inflammable substance by the rays of the sun—tinder, linen, wood, paper, &c. This refers, it is true, to sources of luminous heat; but Melloni has proved by using prisms and lenses of rock-salt—which substance absorbs a smaller amount of heat than any other—that obscure heat is refracted in the same manner as that proceeding from an incandescent source.

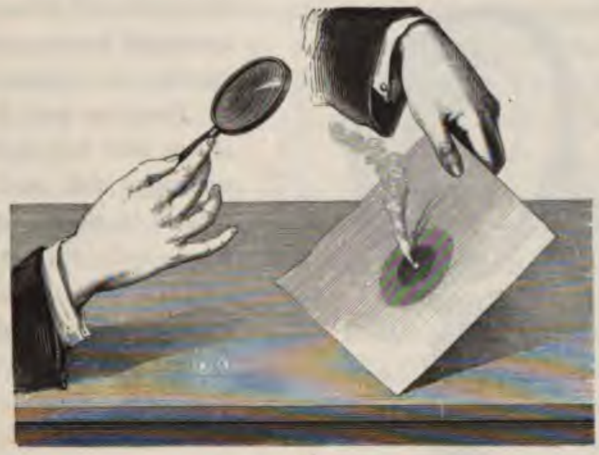

FIG. 306.—Refraction of heat.

The refraction of heat has been used, like its reflection, to produce a very intense heat by the concentration of the rays of the sun. The name of *burning glass* is given to every kind of lens constructed for this purpose, whatever the diathermic substance may be. The power of a burning glass increases with its diameter, and with the shortness of the radii of the spheres to which the surfaces of the lens belong. Tschirnhausen, celebrated for the construction of burning mirrors of great power, made burning glasses nearly a metre in diameter, with which he succeeded in melting metals, and vitrifying mineral substances. Buffon obtained the same results with an echelon lens,—that is, a lens, one surface of which is plane, while the other is cut into concentric rings. The curvature of each of these rings is calculated so that all the solar rays falling on the surface converge to the same point (Fig. 307). In an apparatus of this kind, the thickness of the glass being less than in an ordinary lens of the same aperture, less heat is absorbed, and the calorific effect at the focus is consequently more intense.

Burning glasses have also been constructed with various liquids, the lens being formed of two convex glasses, enclosing a cavity which contains the liquid employed. Of these we must quote the burning glass constructed in the last century by Bernières and Trudaine; it was four feet (1·33 m.) in diameter, and had a focal length of eight feet: when filled with turpentine and exposed to the solar rays, calorific effects of extraordinary intensity were obtained.

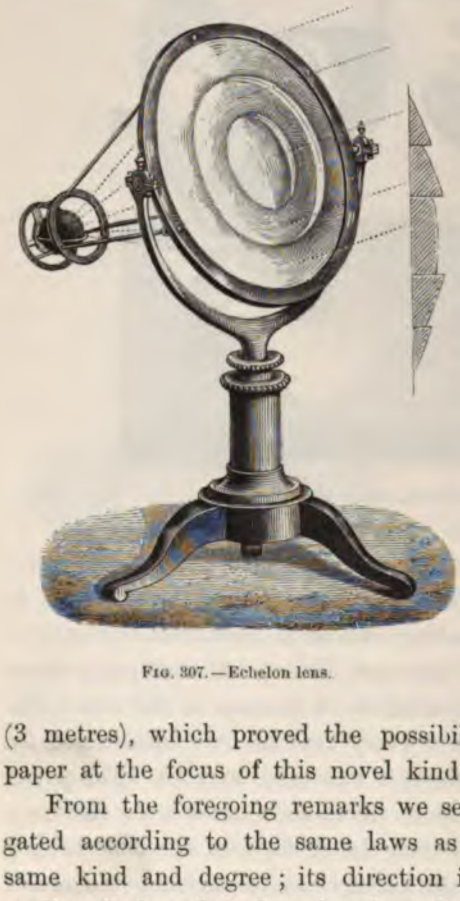
FIG. 307.—Echelon lens.

We have most of us heard that sailors, during voyages to the frozen regions of the poles, have been able to use lenses of ice to procure fire. In England very interesting experiments were made with an ice lens of great diameter (3 metres), which proved the possibility of igniting powder and paper at the focus of this novel kind of burning glass.

From the foregoing remarks we see that radiant heat is propagated according to the same laws as light; its velocity is of the same kind and degree; its direction is rectilinear in homogeneous media; it is reflected and refracted similarly. The analogy has become still more striking since the discovery that heat undergoes double refraction in bi-refractive media; and lastly, that it is also polarized by reflection, and by simple and double refraction. It is probable, therefore, that the calorific radiations do not differ essentially from luminous radiations, that both are due to the same cause, viz. to vibrations of the ether; but, whilst the disturbance produced by the motion of the luminous waves affects the organ of sight alone, that which proceeds from heat-waves, instead of giving us the sensation of light, produces the sensation of heat. Calorific and luminous radiations have even been considered as possessing no other difference, except a greater or less rapidity of the vibratory movement which gives rise to them. Thus the longest undulations or the least refrangible rays—these expressions are equivalent—would constitute the heat-rays, the obscure radiations; then increasing from a certain limit of rapidity, the vibrations, without ceasing to produce heat, would impress the retina in the form of light.

The theoretical ideas which assign a common origin to phenomena apparently so different, and which are so, indeed, to our senses, is becoming more and more plausible. The old hypothesis, which made heat, light, electricity, and magnetism so many real and distinct agents having a separate existence, is almost abandoned. We shall soon see, in regard to heat, other proofs in favour of the new theory, which show that heat is transformed into motion, and motion into heat; a transformation incapable of being explained by the hypothesis that caloric is a substance.

All bodies, whatever may be their temperature, emit or radiate heat. We have described the experiment which proves that this emission takes place with obscure heat as well as with luminous heat. If, then, two or more bodies are in the presence of each other, they will mutually radiate one towards the other, and we know that the heat, received thus by each of them, will be partly reflected or diffused, partly transmitted through its substance, and partly absorbed. It is this last portion only of the heat which has fallen on the surface of a body which, being transmitted from molecule to molecule, that is by conduction, influences its temperature.

When bodies which are near together and confined in a small space are of unequal temperatures, experiment shows that the hottest gradually cool while the others become warmer. At the end of a certain time equilibrium of temperature is established, which proves that the interchange of heat ceases, or rather that it results in an exact compensation between the losses and gains undergone by each of them: the quantities of absorbed and of radiated heat are then equal to each other. This last hypothesis, which is generally admitted, is expressed by saying that the *absorbing power* and the *emissive* or *radiating power* of a body are equal to each other. Moreover, the hypothesis has been verified by experiment, as regards temperatures not exceeding 300°. Of this more presently.

The temperature of a source of heat influences the rapidity with which it is cooled by radiation. Generally speaking, the higher the temperature, the more considerable is the emission, other circumstances remaining the same. This result may be proved by enclosing the source of heat in a vacuum or in a space filled with a gas, provided that the temperature be higher than that of the walls of the enclosure, the rapidity of the cooling being also greater as the excess of temperature itself is greater.

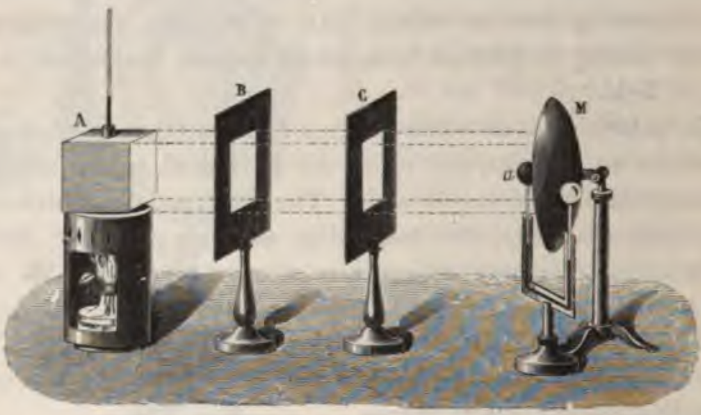

FIG. 308.—Measure of the emissive powers of bodies. Experiment with Leslie's cube.

Emissive power depends also on the nature of the surface by which the radiation is effected. Leslie proved the inequality of the emissive power of different bodies in the following manner:—

As a source of heat, he took hollow cubes, the lateral faces of which were formed of the substances whose emissive powers he desired to compare; he then filled them with boiling water, which was kept at a temperature of 100° by the heat of a spirit-lamp. Each face of the cube A (Fig. 308) was turned successively towards a concave mirror M, at the focus *a* of which was placed one of the bulbs of his differential thermometer. To limit the rays of heat which fell on the mirror, Leslie placed two screens B, C, pierced with wide apertures in the common axis of the mirror and cube, as shown in Fig. 308. The action of the radiated heat produced a difference of level in the two limbs of the differential thermometer, which became stationary at the end of a few seconds. Operating in the same manner with the different faces of his cubes, Leslie proved that the nature of the radiating surface has a considerable influence on the emissive power; and, as it has been proved that the emissive powers of two bodies are proportional to the excess of temperature of the two bulbs of the apparatus, he could form a comparative table of their values for one temperature of the heat-source.

Since Leslie's time, the radiating powers of a great number of bodies have been measured with other apparatus, and his result, that lamp-black and white lead are the two substances which possess the greatest amount of radiating power, has been verified. If we represent the emissive powers of these substances by 100, the emissive powers of the following substances, at the temperature of 100°, are as follows:—

Lamp-black . . .	100	Steel	17
White lead . . .	100	Platinum	17
Paper	98	Polished brass . . .	7
Glass	90	Red copper	7
Indian ink . . .	85	Polished gold . . .	3
Gum-lac	72	Polished silver . .	3

We thus see that the metals possess the least emissive power. It was once imagined that bodies of bright colours radiated heat to a less extent than those of a dull and dark colour, but the foregoing table disproves this; for white lead radiates as much as lamp-black. The degree of polish of the surface of a body, a metal for instance, influences its radiating power: in the case of a beaten or laminated plate, if it is roughened its radiating power is increased; on the contrary, it is diminished if the plate is of cast metal; which leads to the supposition that the emissive power is in the inverse ratio of the density of the superficial strata.

The preceding results account for a fact, which is easily proved, that polished metal vessels, especially silver ones, preserve the heat of the liquids contained in them for a long time; but if this surface is unburnished, and especially if it be covered with lamp-black, the radiation becomes very intense, and the cooling of the liquid takes place rapidly.

From a consideration of the radiating power of different substances let us pass to their reflecting power. And in the first place we may remark that, in the case of a body which is not transparent to heat or which is adiathermanous, of 100 heat-rays falling on its surface, perhaps 20 will be absorbed; while all the others, to the number of 80, will be reflected. Now, as the absorbing power is itself equal to the emissive power, by a very simple calculation the reflecting powers of bodies can be found without having recourse to experiments. At the same time we must not forget that experiment has led to the preceding reasoning; and in physics, it is always more instructive to learn anything experimentally, both as regards the explanation of facts and the verification of laws.

Leslie compared the reflecting power of different substances, by modifying the apparatus which he used for the study of their radiating powers; but we prefer the apparatus used by Melloni, as many other researches connected with heat can be made with it.

The following is a description of it:—

A series of bars of different metals, usually bismuth and antimony, B, A, . . . are soldered together at their extremities, and they are arranged in such a manner that all the even junctures are on one side, and all the odd ones on the other, as in Fig. 309. The two extreme bars of the series, one bismuth and the other antimony, are connected by a metal wire; this forms a *thermo-electric pile*. Whenever there is a difference of temperature between the even and the odd joints, an electric current is produced, either in one direction or the other, but always passing from the bismuth to the antimony, on the side which is at the highest temperature. Generally a certain

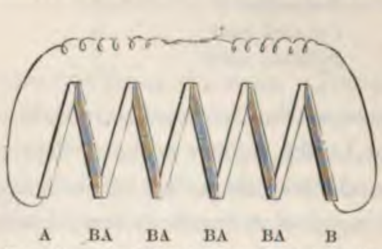

FIG. 309.—Elements of the thermo-electric pile.

number of similar elements are united in a bundle, to which the form of a rectangular prism is given, so that both faces are visible, one formed by the even number of joints, the other by the uneven.

Whenever one or other of the faces of the pile is heated by calorific radiation, the current will be produced; and we must now consider how its existence can be proved. The two conducting wires are wound round the frame of a galvanometer—the description of which will be found in Book VI., which is devoted to Electricity—and the current acts on the magnetic needle, causing it to deviate either in one direction or in the other, according to the direction of the current. The extent of the deviation can then be read on the dial of the galvanometer, and this shows the intensity of the current, and, afterwards, the difference of temperature of the two faces of this pile. The thermo-electric pile thus constituted is an instrument of great sensibility: if we touch one of the faces with the finger, or blow a puff of warm air upon it, it is sufficient to cause the needle of the galvanometer to be considerably deviated; on touching the same face with a cold body, deviation takes place in the contrary direction. Melloni employed the thermo-electric pile for the measure-

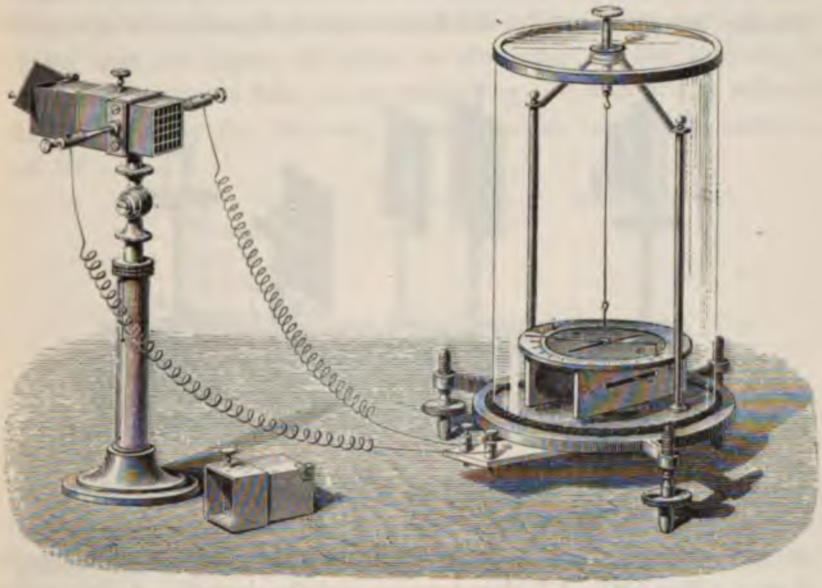

FIG. 310.—Thermo-electric pile for the study of the phenomena of heat.

ment of the *reflecting powers* of different bodies, in the following manner:—

At A (Fig. 311) a Locatelli lamp, which is a heat-source of constant intensity, was placed; B and C are two screens, one entirely opaque, the other having an aperture or diaphragm, thus allowing heat-rays from the lamp to pass through it, when the screen B is removed.

On the stand D, a plate of the reflecting substance to be examined is placed, and at E is the thermo-electric pile, moving on a scale H H′, which can be moved round the point H, so that the face of the pile can be placed in the direction of the reflected calorific rays. Before placing the plate on its stand, the scale is turned round the point H, and placed in a line with the scale which supports the pieces A, B, C. The screen B is then lowered, and the deviation of the needle of the galvanometer is measured, which gives the intensity of a ray of heat radiated directly from the lamp to the pile, at a distance equal to the total lengths of the scales. When the first measurement has been effected, a second is made in order to give the intensity of the reflected ray, and for this purpose the different parts of the apparatus are placed as shown in the figure, the reflecting plate being on its support, and the pile protected from direct radiation by means of a large screen. On lowering the screen B, the rays emanating from the source fall on the plate, are there reflected, and strike against the face of the pile, after having traversed the same

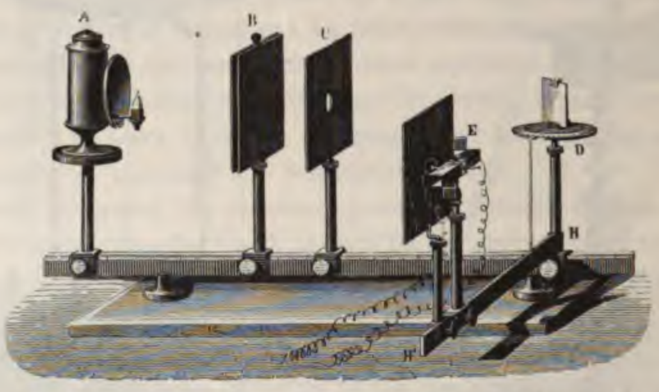

FIG. 311.—Apparatus used by Melloni to measure the reflecting power of bodies.

distance as the direct rays did in the first experiment. The needle of the galvanometer is deviated to a certain extent, and the relationship of the two deviations gives the reflecting power of the substance.

MM. La Provostaye and Desains have continued Melloni's researches, and experimented on a great number of substances; they have measured their reflecting powers under different incidences, varying the natures of the source of heat. They have discovered that with any one body the reflecting power remains nearly constant, from the normal incidence to an incidence of 30°; but afterwards it increases rapidly, in proportion as the angle of incidence increases. The reflecting powers of metals remain nearly constant for each of them, in whatever manner their surfaces have been worked, provided that the degree of polish is the same. If the intensity of the incident ray of heat be represented by 100, that of the reflected ray is given by the following numbers, which refer to an incidence of 50°:—

	Reflecting powers.	Radiating powers.
Polished silver	97	3
Gold	95	3
Red copper	93	7
Polished brass	93	7
Platinum	83	17
Steel	83	17
Glass	10	90
Lamp-black	0	100

By comparing these numbers with those which measure the radiating or emissive powers of the same substances, shown in the second column, we find a proof of what has been before stated, viz. that the radiating and absorbing powers of a body must be equal; for the radiating, like the absorbing, power is the complement of the reflecting power, at least for bodies which are not transparent to radiant heat, and if we make due allowance for the diffused heat.

Polished metals possess the greatest amount of reflecting power; when their surfaces are unburnished or rough, the heat-rays are reflected in every direction, and the proportion of heat reflected in a regular manner diminishes considerably as the proportion of diffused heat increases. This phenomenon is analogous to that observed under the same conditions in the case of light.

Leslie and Melloni also compared, by means of the two apparatus before described, the *absorbing powers* of bodies; that is to say, the proportion of heat emitted from a constant source which enters them and raises their temperature. They found that, in this respect, the order of classification of the various substances is the same as if they had been arranged according to their emissive powers; a result which confirms, to a certain extent, the equality of these two powers proved by the reasoning adopted in the case of equilibrium of temperature. We owe to Leslie the experimental determination of the fact that good reflectors of heat are bad radiators.

What has been aptly termed the *Theory of Exchanges* of radiant heat,—a branch of the subject which has been investigated by Prevost, Provostaye, Desains, Balfour Stewart, and Kirchhoff,—may be stated as follows:—

I. If an enclosure be kept at a uniform temperature, any substance in it will at last attain that temperature.
II. All bodies are constantly giving out radiant heat independently of the temperature of the bodies which surround them.
III. Therefore, when a body is kept at a uniform temperature, it receives back as much heat as it gives out, *i.e.* its absorption is equal to its radiation.

This theory not only applies to the quantity of heat but to its quality. That is, it holds good not only in the case of dark rays, but to particular rays located in a particular part of the spectrum of a body visibly luminous, as the spectrum of the light emitted by such a body is built up of both heat-rays and light-rays, as we have seen.

Hence to these statements we must now add, according to the researches of Balfour Stewart and Kirchhoff:—

IV. Bodies when cold absorb the same rays which they give out when hot.

It will be seen that this is the same statement which we have already made concerning light; it is in fact the basis of spectrum analysis.

The influence of colour on the absorption of heat-rays has been shown by Franklin's experiments. This illustrious physicist placed pieces of differently coloured stuffs on the snow, and left them for some time exposed to solar heat; they absorbed the heat-rays, became warm, melted the snow beneath them, and thus sank to various depths, and deeper in proportion as the colour was darker. From this result it was thought that bodies of light colours are bad absorbers, and this again justified the supposed identity of rays of light and rays of heat. But Tyndall has recently proved that this conclusion is not quite exact. According to this physicist, the nature of the source of heat must be taken into account; obscure heat-rays are not affected in the same way as luminous heat-rays. The diathermanous power of substances must also be considered. Thus, having taken two cards, one covered with white powdered alum and the other with black powdered iodine, and having exposed both to the fire, he found that the iodized card scarcely warmed at all, while the card covered with alum beçame extremely warm; he explains this difference by the diathermanous property which iodine possesses to such a high degree: the radiant heat penetrates the powder and is reflected on the limiting surface of the molecules, without being absorbed by them. Moreover, a piece of amorphous, and almost black, phosphorus, placed at the focus of the electric light, cannot be ignited, whilst the same arrangement nearly instantaneously raises platinum to a white heat. Tyndall attributed this curious effect to the diathermancy of the phosphorus.

This last property, possessed by certain substances, in virtue of which they can be traversed by heat-rays without absorbing them, in other words without their temperature being raised, exists in the most marked manner in rock-salt. Of 1,000 rays which reach the surface of a plate of this substance, 923 are transmitted; the 77 rays which do not pass are reflected from the two faces of the plate; consequently, there is no absorption. This remarkable result, discovered by Melloni, remains the same, whatever may be the nature of the heat-rays, whether luminous or obscure.

Alum and glass are only diathermanous as regards the radiations of luminous heat; they arrest rays of obscure heat: this is also the case with Iceland spar, rock-crystal, and ice. The thickness of the plates has an influence on the absorption as on the transmission of heat-rays; but this influence does not increase in proportion to the thickness. Thus of 100 rays which reach two diathermanous surfaces, one having double the thickness of the other, 62 rays pass through the thinner, and 58 through the other; a plate quadruple the thickness of the first allows 55 rays to pass.

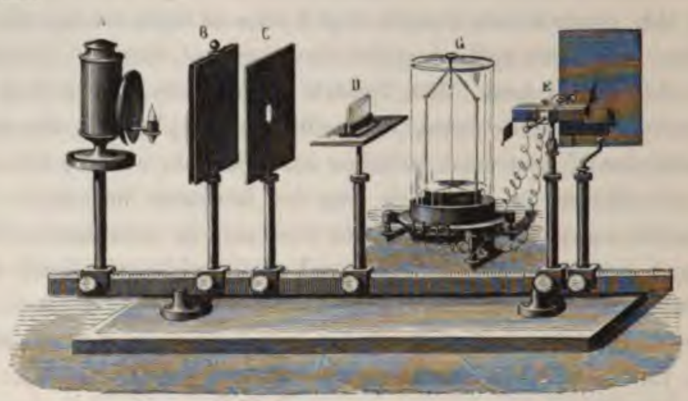

FIG. 312.—Melloni's apparatus for measuring the diathermanous power of bodies.

The comparison of the diathermanous powers of different substances is made by means of Melloni's apparatus, arranged as in Fig. 312. A plate of the substance the diathermanous power of which is to be measured, is supported on a stand D. The thermoelectric pile is placed at E, in the direction of the rays of heat which traverse the aperture made in the screen C. The deviation of the

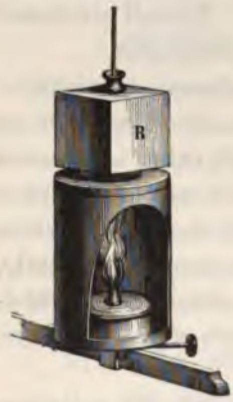

FIG. 313.—Cube of boiling water.

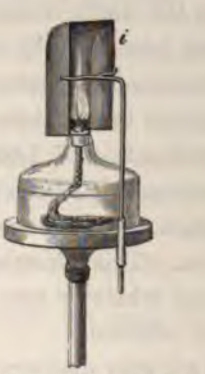

FIG. 314.—Plate of blackened copper heated to 400°.

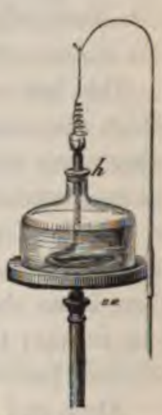

FIG. 315.—Incandescent spiral of platinum.

needle of the galvanometer, produced by the direct rays without the interposition of the plate, is first ascertained; the plate is then placed on its stand, and the deviation produced by the same rays traversing the plate is noted. The relation of these two deviations gives the diathermanous power of the substance.

To study the influence of the nature of the heat-source, Melloni substituted in place of Locatelli's lamp a cube of boiling water, a plate of blackened copper, or an incandescent spiral of platinum. These different heat-sources are represented in Figs. 313, 314, and 315. In the experiments he made on this subject, Melloni took care, in order to compare the results, to place these different sources at such distances from the pile, that the direct rays of heat produced the same deviations on the needle of the galvanometer.

The following table shows the influence of the nature of the source of heat on the transmission or on the diathermanous power of different substances:—

	Locatelli's lamp.	Cube of water at 100°.	Copper at 400°.	Incandescent platinum.
Direct radiation	100	100	100	100
Rock-salt	92	92	92	92
Iceland spar	39	28	6	0
Glass	39	24	6	0
Rock-crystal	37	28	6	0
Alum	9	2	0	0
Ice	6	0	0	0

From these experiments we conclude that, as there are different rays of light, so also there are different rays of heat which bodies absorb and transmit in different proportions, nearly in the same way as transparent bodies absorb some colours and allow others to pass. Speaking of this property, Melloni used the word *thermochroism*, derived from two words, the first signifying *heat* and the second *colour*.

In terminating the foregoing remarks concerning radiant heat, we may enunciate the following law relating to the decrease of intensity with an increase of distance. As with light, the intensity of radiant heat varies inversely as the square of the distance. A very simple experiment, which we have borrowed from Tyndall's work on Heat, proves the truth of this law, which may be deduced by calculation.

One face of the thermo-electric pile is furnished with a cone which limits the dimensions of the sheaf of heat-rays, and which, covered on the inside with black paper, can only reflect the heat which falls obliquely on its inner surface. For the source of radiant heat, a tin vessel filled with boiling water is used, one face of which is covered with lamp-black; this surface we use to prove the law, by radiation towards the pile. The pile furnished with its cone is placed opposite the vessel, at a given distance S O (Fig. 316); the needle of the galvanometer is deviated to a certain extent; the pile is then removed to double the distance S′ O; the position of the needle of the galvanometer remains constant; and this is the case for any other distance. For each of these positions, the total effect of radiation is therefore the same; but the parts of the surface of the vessel which send out rays of heat into the cone are greater and greater; these are circles whose diameters A B, A′ B, increase in proportion to the distance of the pile from the vessel, and whose surfaces from that time continue to increase as the squares of these same distances. It is therefore necessary that the intensity of radiation diminishes in the ratio of these same squares, in order that the effect produced on the pile may remain constant. In a word, the augmentation of the efficacious radiating surface is exactly compensated for by the diminution of the intensity with the distance; it is thus that the law has been proved.

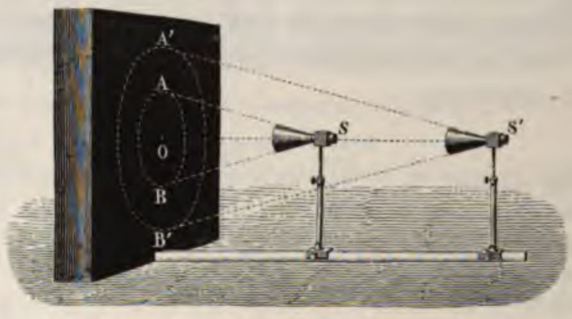

FIG. 316.—Intensity of radiant heat. Law of the squares of the distances.

CHAPTER V.

TRANSMISSION OF HEAT BY CONDUCTION.

Slow transmission of heat in the interior of bodies—Unequal conductivity of solids—Conductivity of metals, crystals, and non-homogeneous bodies—Propagation of heat in liquids and gases; it is principally effected by transport or convection—Slight conductivity of liquid and gaseous bodies.

WE have already seen that, if we hold a bar of iron, one end of which is placed in the fire, in the hand, the heat of the fire is communicated to the metal, and is transmitted from molecule to molecule along the bar; after a short time, the temperature rises so high that it commences to burn our hand, and obliges us to remove it from the bar. If, instead of being iron, the bar, still of the same diameter and length, is of another metal, a similar effect would be produced; but we observe that the length of time which the heat takes to travel along the bar, and to heat it at any given distance from the end to the same temperature, varies with the nature of the bar. The following simple experiment will prove the difference which we have pointed out:—

Let us take two bars of equal dimensions, one of copper, the other of iron, and fix small balls of wood by means of wax at equal distances from the extremities of each; now, if we place the bars end to end and heat the extremities in contact by means of the flame of a spirit-lamp placed at the point of junction, we shall see the balls fall one after the other, as the wax is melted by the heat which is transmitted by means of conduction along each of the bars. But at the end of a certain time, the number of balls which have fallen from the copper bar will be found to be greater than the number of balls which have fallen from the iron bar. Moreover, two balls situated at the same distance from the source of heat but on different bars, do not fall at the same instant.

We will for the present leave the consideration of the rapidity with which heat is transmitted along each bar, and study the first effect, viz. the comparative distance at which a certain degree of temperature (here it is that of the fusion of wax) can be most quickly attained by the two metals. Copper, in which we have found this distance to be first attained, is said to be a *better conductor* of heat than iron.

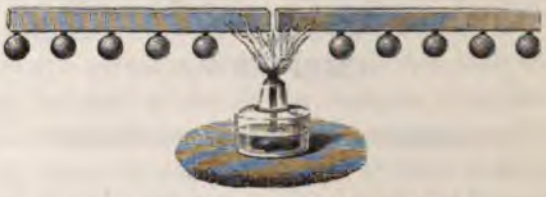

FIG. 317.—Unequal conductivities of copper and iron.

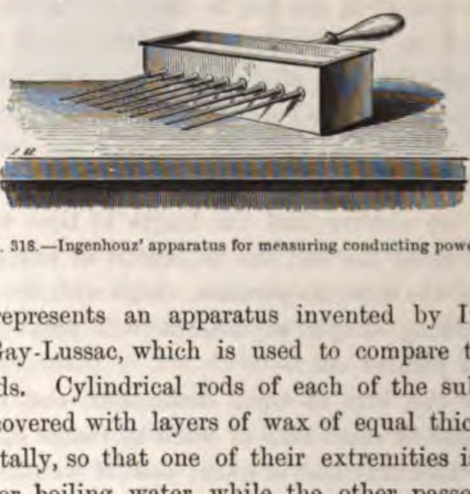

FIG. 318.—Ingenhouz' apparatus for measuring conducting powers.

Fig. 318 represents an apparatus invented by Ingenhouz and modified by Gay-Lussac, which is used to compare the conducting powers of solids. Cylindrical rods of each of the substances to be compared are covered with layers of wax of equal thickness, and are placed horizontally, so that one of their extremities is immersed in a bath of oil or boiling water, while the other passes through the sides of the vessel which contains the liquid. The heat of the liquid is transmitted along each rod, and melts the wax at distances which are greater as the conductivity of the substance increases. Other processes have been devised for the measurement of the conducting powers of solids; but the one we have just described is sufficient to show how different bodies can be arranged in the order of their conductivity. The following is the order and degree of conductivity of the principal metals:—

Silver	1,000	Iron	119
Copper	776	Steel	116
Gold	532	Lead	85
Brass	236	Platinum	84
Zinc	190	Palladium	63
Tin	145	Bismuth	18

Of all solid bodies metals are the best conductors of heat, always excepting bismuth. Stone, glass, and marble are much less so than metals; lastly, wood-charcoal prepared at a low temperature, that is to say not calcined, and organic substances generally, pulpy fruits and plants, and the tissues of animals and vegetables, are bad conductors. The preceding numbers indicate the great difference in the conductivities of metals. This difference may be illustrated in a very simple way, by plunging two spoons, one of German silver and the other of pure silver, into the same vessel of hot water. After a little time the free end of the silver spoon is found to be much hotter than that of its neighbour; and if pieces of phosphorus be placed on the ends of the spoons, that on the silver will fuse and ignite in a very short time, while the heat transmitted through the other spoon will never reach an intensity sufficient to ignite the phosphorus.

The reason of this is accounted for by the difference between the conducting power of the silver and that of the German silver; for the first is represented by 1,000, the second by 60. The following experiment demonstrates that the conductibility of a substance does not depend on the rapidity with which heat is transmitted through its interior. Two short cylinders of the same volume, one of iron, the other of bismuth, have each one of their extremities coated with white wax; they are then placed on the cover of a vessel filled with hot water, their waxed ends being uppermost. The heat of the vessel is transmitted through each cylinder, and the wax on both will melt; but that which covers the bismuth will melt first. Nevertheless, the conductivity of bismuth, according to the foregoing table, is six times less than that of iron. What therefore can be the reason of the phenomenon described? It is due to the fact, that to raise the two metals of the same weight to the same temperature, about four times more heat is required for iron than for bismuth; the heat received by the iron is therefore in great part expended in raising its temperature, and this explains the relative slowness with which the transmission through its mass takes place. To rightly observe the difference between the conducting powers of iron and bismuth, it is necessary to take two bars of the same diameter, to measure the distances from the source of heat of the points which possess the same temperature at the moment of equilibrium, and to take the squares of the numbers which measure these distances, which will give the relative conducting powers.

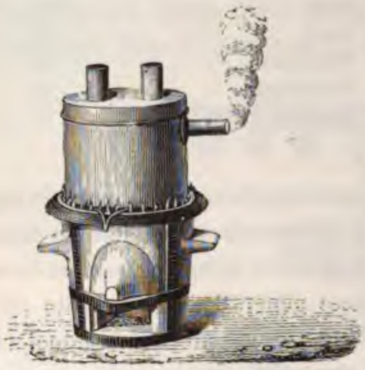

FIG. 319.—Experiment on the conductivity of iron compared with that of bismuth

The foregoing remarks refer to homogeneous bodies. In solids whose structure is not the same in every direction—for example, doubly refracting crystals, Iceland spar, quartz, &c.—the conductivity varies with the *direction* of transmission of the heat. There is a complete analogy between the mode in which heat is propagated in these bodies, and that which relates to the movement of light. Thus, let us take two plates of quartz, one cut parallel and the other perpendicular to the optic axis; coat both of the sections with wax, and pierce them with a hole, through which a wire heated by an electric current is passed: on passing the current we observe that the wax melts around the wire; but whilst the stratum limiting the melted wax is an ellipse in the first plate, in the second it is a perfect circle (Fig. 320), which proves the unequal conductivity in the two directions. The conductivity of wood is greatest in the direction of the fibres, and much less in a direction perpendicular to this.

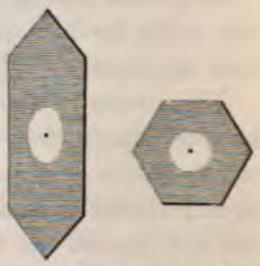

FIG. 320.—Unequal conductivity of quartz in different directions.

The unequal conductivity of different solids is utilized in many ways. Tools and metal utensils, which require to be submitted to a high temperature, are furnished with non-conducting handles—of wood or ivory, for instance—which almost entirely stop the transmission of heat. Cotton, silk, and especially woollen fabrics, are bad conductors; they are therefore useful for preserving the body from excessive heat or cold. In summer, they prevent the exterior heat from penetrating to our bodies; and in winter, on the contrary, the heat of the body is retained on account of the difficulty of its transmission through thick clothes. Moreover, it is not alone the substance of which they are composed which gives this property to the fabric, for the mode of manufacture also influences it. Between the threads, air is interposed, which remains at rest, and, like all gases in a state of rest, it conducts heat very badly; heat therefore passes with great difficulty through the fabric. Eider down preserves heat much better than a closely made and heavier woollen coverlet would do.

We might multiply these examples to any extent, but will confine ourselves to two or three curious experiments based on the differences of conductivity of solids. A metal ball is tightly wrapped up in fine cloth, in such a manner that the contact is close; we then take a coal from the fire and place it on the ball thus enveloped, the fabric remains intact; and if, to increase its combustion, the coal is blown upon, the cloth is not burnt. The reason of this is that the heat received by the linen is immediately monopolized by the good-conducting metal, and disseminated through its mass.

If before lighting a gas-lamp a piece of fine wire-gauze is placed above the jet, and the gas then turned on, it will spread below and above the gauze. If it is lighted underneath, the combustion remains confined to the lower part of the jet of gas; if, on the contrary, it is lighted above, the upper part of the jet will alone continue to burn (Fig. 321). In both instances, the interposition of the wire-gauze is sufficient to limit the combustion, and the reason is obvious: the meshes of the gauze form an excellent conductor of the heat developed, which spreads rapidly over the wire, and does not allow the flame a sufficiently high temperature for its existence on the other side of the gauze. An important application of this property of metallic gauzes exists in Davy's *safety lamps*, which are used by miners. The metallic netting which envelopes the light prevents the ignition and explosion of the fire-damp,—a dangerous gas which escapes plentifully into coal-pits.

Asbestos and amianthus are two silky mineral substances, noted for their incombustibility. They are very bad conductors of heat, and with a glove of amianthus a red-hot ball may be held in the hand without danger of burning. In this instance, the heat cannot be transmitted, it is intercepted; in the preceding example it is, on the contrary, rapidly absorbed; in both cases its transmission by means of conduction is limited.

The experiments which have been made in order to measure the conductivity of liquids and gases prove that it is very slight. Nevertheless, heat is transmitted with some rapidity through these media; it is, however, transmitted not by *conduction* but by *convection*, that is to say, by direct transport of the heated parts. The cause of these movements may be easily understood; when a liquid is heated, its density diminishes; then, as a consequence of the principle of Archimedes, it tends to rise and to displace the denser strata above it. This happens, when a liquid is heated at the bottom of the vessel which contains it; if the liquid is heated laterally, the currents which are established start only from the sides, instead of starting from all parts of the bottom of the vessel; the heating in this case is much less rapid. The existence of currents is easily proved, if a material of the same density as the liquid is mixed with it, such, for example, as sawdust. This remains suspended in water, and on heating the vessel the movement of the particles can be traced from top to bottom and from bottom to top, proving the existence of currents: the ascending currents proceed from the heated parts, which rise, while the descending currents are due to the denser parts, which take the place of the first. Heat is therefore diffused through the whole liquid, and is thus transmitted.

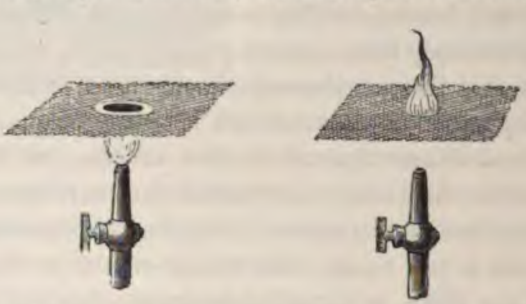
FIG. 321.—Property of metallic gauze; obstacle which it opposes to the propagation of heat.

Nevertheless, liquids possess some actual conductivity, as has been proved by M. Despretz, who heated from above a liquid contained in a cylindrical vessel. Twelve thermometers, the bulbs of which were placed at different heights in the liquid, with their stems outside, indicated decreasing temperatures from the upper strata to the middle of the vessel, which was a metre in height; the six lower thermometers did not rise perceptibly. The conductivity of liquids is thus established, but, as before stated, it is very slight.

The conductivity of gases cannot be established; all that we know is, that they are certainly very bad conductors of heat. Gaseous masses are heated like liquid masses, by transport or convection: in virtue of their great dilatability, as soon as a portion of a gaseous mass is heated, either by radiation or contact, its volume increases, and movements, which quickly heat the different strata, result. The heat is thus conveyed as in liquids, but with still greater rapidity. Again, if the movements of which we speak are confined by enclosing the gas in the interstices existing between thin pieces of fibrous substances, like cotton, wool, unspun silk, down, &c., the gas acquires heat with difficulty, as has been proved by many experiments of Thomson. We have already seen that it is partly owing to the fact of gases being bad conductors of heat when at rest, that clothes preserve the body from losing heat during cold weather.

CHAPTER VI.

CALORIMETRY.—SPECIFIC HEAT OF BODIES.

Definition of a unit of heat—Heat absorbed or disengaged by bodies during variations in their temperature—Specific heat of solids—Latent heat of fusion—Ice-calorimeter—Latent heat of vaporization of water.

WHEN a body is heated or cooled through a certain number of degrees, we say that it gains or loses a certain quantity of heat; but the thermometer which shows us these variations indicates nothing as to the value of this quantity: we must not therefore give the precise etymological sense to the word thermometer. The thermometer measures temperatures, not quantities of heat. We shall find, indeed, that the heat necessary to raise a given weight of a body through a certain number of degrees, varies with the nature and physical condition of the body; beyond certain limits of temperature, it varies also for the same substance.

Before proceeding further, we must explain what is meant by *quantity* of heat. We know nothing of the intimate nature of heat; the analogies which we have endeavoured to establish between radiant heat and light, have induced physicists to imagine that calorific phenomena, like luminous phenomena, are produced by the vibrations of the ether; but the manner in which these vibrations, after penetrating into the interior of bodies, produce changes of volume and condition, is a question which science has not yet solved, and which has only been answered by conjecture. Nevertheless, researches of great importance have placed beyond doubt the important fact that heat can be produced by mechanical means, and, conversely, that it can be transformed again into mechanical work susceptible of being accurately measured; in a word, that heat can be assimilated to force and measured like other physical forces. We shall hereafter endeavour to explain what is understood by the *mechanical equivalent of heat.*

Without passing beyond the domain of heat itself, we will now state how it is possible to compare the quantities of heat which are absorbed or disengaged during variations in the temperature as well as in the changes of condition of solid, liquid, and gaseous bodies. This division of the science of heat is known as *calorimetry.*

A unit of heat, or *calorie,* is the quantity of heat necessary to raise from 0° to 1° centigrade one kilogramme (in England one pound) of water. It is evident therefore that, if a certain number of calories are requisite to raise the temperature of the unit of weight a certain number of degrees, 2, 3, 4, ... more would be required to raise the temperature the same number of degrees of a weight 2, 3, 4 times greater. Therefore the quantities of heat are proportional to the weights. It is also considered as established, that the heat requisite to raise the temperature of a given weight through a certain number of degrees, is equal to that which it disengages on returning to its initial temperature. A very simple experiment also proves to us that the quantity of heat absorbed during a certain elevation of temperature is perceptibly constant, whatever may be the initial temperature.

Into a vessel which has been heated to 25°, a kilogramme of water at 0° is poured, and a second at 50°; then, after having rapidly stirred the mixture, a thermometer on being plunged into it shows the temperature of the mixture to be 25°. Thus the heat, transferred by the kilogramme of water at 50° to the kilogramme at 0°, raises the temperature of the second kilogramme to 25°; at the same time, the loss of heat undergone by the first has lowered its temperature from 50° to 25°. Finally, this experiment proves that the heat necessary to raise a definite weight of water from 0° to 25°, would raise the same weight of water from 25° to 50°. The initial temperature has therefore no influence on the quantity of heat absorbed.

This, however, is only true within certain limits, which vary with different substances: thus, two kilogrammes of mercury, one at 200°, the other at 0°, mixed together, give two kilogrammes of mercury, not at 100°, the mean temperature between the two extremes, but at 102°·85, a higher temperature than the mean. Beyond 100°, mercury absorbs or disengages more heat for a like variation of temperature than below 100°. Lastly, a third experiment shows that the quantities of heat which we have just compared, vary with the nature of the substances. If we mix separately one kilogramme of water at 0° with a similar weight of mercury or essence of turpentine at 100°, or place in it a kilogramme of copper at 100°, a gain of heat for the water and loss for the other substances will, as in the previous instances, result; and in each experiment it will be obvious that the gain will be equal to the loss. But in the first instance the temperature of the mixture will be 3°·2, in the second 30°, and in the third case 8°·6. We see therefore how much heat is requisite to produce the same variation of temperature in equal weights of different substances. This is explained by saying that every substance has a *calorific capacity*, or *specific heat*, belonging to it, and specific heat may be defined as the quantity of heat which is necessary to raise the temperature of a kilogramme (or pound) of a substance from 0° to 1°. This quantity of heat is expressed in *calories* or heat-units, which evidently amounts to taking for unity the specific heat of water.

Various methods have been employed by physicists for the measurement of the specific heat of solids. One of these—the method of mixtures—consists in plunging the body, the temperature of which is known, into a bath of water or any other liquid at an equally fixed temperature: when the temperature of the mixture has become stationary, it is measured, and, by a simple calculation,[1] the relation of the specific heats of the solid and liquid is obtained. This method is applied equally to liquids. Certain precautions are taken when the bodies placed in contact exercise a chemical action on each other; moreover, the heat absorbed by the vessel is noted by the thermometer itself, and lastly the losses caused by radiation. The following is a table giving the specific heats of different solid, liquid, and gaseous bodies; it proves that water of all substances (with the exception of hydrogen, the specific heat of which is three times that of water) absorbs or disengages the greatest quantity of heat for equal variations of temperature:—

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[1] This calculation consists in solving an equation—the first part of which expresses the quantity of heat lost by the body, and consequently transferred to the bath and vessel; the second comprising two terms—the first, the heat gained by the liquid; the second, the heat gained by the vessel which contains it. It is evident that, putting aside the external radiation of the liquid and vessel, the loss and the gains are compensated: hence the equation and solution of the problem.

Substances.	Specific heat.
Water	1·000
Hydrogen	3·294
Essence of turpentine	0·426
Air	0·207
Sulphur	0·203
Glass	0·198
Iron	0·114
Copper	0·095
Silver	0·057
Tin	0·056
Mercury	0·033
Gold	0·032
Platinum	0·032
Lead	0·031
Bismuth	0·031

But we must not forget that these numbers represent the quantities of heat necessary to raise equal weights of these bodies from 0° to 1°, and that they only remain constant within certain limits of temperature. They vary but little from 0° to 100°; but this is no longer the case at higher temperatures. The specific heat of mercury, for instance, which is 0·033 within these limits, becomes 0·035 beyond 100°. The physical condition of bodies also causes the specific heat of the same substance to vary; in the solid state it is less than in the liquid state, and in the gaseous state it regains perceptibly the value which it had in the solid state: thus the capacity of ice, which is nearly equal to that of steam, is scarcely half that of water. When the density of a metal is increased, by hammering for example, its specific heat is diminished. This explains, to a certain extent, a result deduced from the preceding table, viz. that the densest bodies have generally the smallest capacity for heat.

Dulong and Petit discovered a remarkable law, which has been verified by M. Regnault in his beautiful researches on the specific heats of bodies. It is well known that chemists consider simple bodies as formed of irreducible parts or atoms, the weight of which is called the chemical equivalent of the body. The weight of the atom of hydrogen being taken as unity, that of an atom of mercury is 100, that of sulphur 16, and so on. This being granted, let us now inquire what quantity of heat will be necessary to raise the temperature of an atom of sulphur 1°; and what quantity likewise will be absorbed by an atom of mercury to raise its temperature 1°. It is evident from the foregoing, that we must multiply the weights 100 and 16 of each atom by the specific heat of the simple body to which it belongs; that is to say, by 0·033 and 0·203: the products will be proportional to the quantities of heat sought. Now, 100 × 0·033 gives 3·3, and 16 × 0·203 gives 3·248: the products are thus sensibly equal, and the same happens if we take any other two simple bodies. This law may be enunciated as follows :—The same quantity of heat is required to raise the temperature of an atom of any simple body the same number of degrees; or, again, the *atomic specific heat* is the same for all substances.

We have seen that the specific heat of water is nearly four times greater than that of air; thence it follows that 1,000 kilogrammes of water, on being cooled 1°, disengage an amount of heat sufficient to raise the temperature of 4,000 kilogrammes of air 1°. But 4,000 kilogrammes of air occupy, under the normal barometric pressure and at 0°, a volume 770 times that of a like weight of water; that is to say, a volume of 3,080 cubic metres: the consequences of which fact are thus explained by Tyndall in his work on Heat :—

"The vast influence which the ocean must exert, as a moderator of climate, here suggests itself. The heat of summer is stored up in the ocean, and slowly given out during the winter; hence one cause of the absence of extremes in an island climate. The summer of the island can never attain the fervid heat of the continental summer, nor can the winter of the island be so severe as the continental winter. In various parts of the Continent, fruits grow which our summers cannot ripen; but in these same parts our evergreens are unknown; they cannot live through the winter cold. Winter in Iceland is, as a general rule, milder than in Lombardy."

In quoting these remarks, we must not forget that the particular facts related by Tyndall do not depend only on the vicinity of the ocean and the high specific heat of water, but also on the elevation of temperature in Iceland by the great lukewarm current of water known as the Gulf Stream.

In describing the phenomena of fusion of solids, and the vaporization of liquids, we insisted on the general fact, that the temperatures of the melting and of the boiling point are fixed for each body, independently of the intensity of the source of heat which determines the result, or the rapidity with which these changes of condition are effected. These temperatures are the same, moreover, as those of the inverse phenomena of solidification of liquids and liquefaction of vapours. Thus, when a piece of ice melts, its temperature remains constant at 0°, and all the heat furnished by the fire, whatever may be its intensity, is consumed in reducing the ice to the liquid condition and in maintaining this condition. We have here, therefore, a quantity of heat absorbed by a body which does not raise its temperature, and consequently does not become sensible to the thermometer. On this account it is called *latent heat.* It is the latent heat of *fusion* or *liquidity,* or, better, the latent heat of *elasticity,* according as it refers to the passage from the solid to the liquid condition, or to the passage from the liquid to the gaseous condition. It is very evident, therefore, that the heat which is absorbed in these two instances is disengaged when the substance returns to its primitive condition. The latent heat of different substances has been determined by methods analogous to those which are employed in the case of specific heat. We shall confine ourselves here to the results obtained in the melting of ice, because it will enable us to describe another process for determining the specific heat of bodies.

It has been found that the latent heat of fusion of ice is 79·25 calories; that is to say, that the quantity of heat absorbed by a kilogramme of ice during melting, would be sufficient to raise 79·25 kilogrammes of water from 0° to the temperature of 1°; or again, to raise a kilogramme of water from 0° to 79°·25. Therefore, when a kilogramme of ice at 0° is melted in a kilogramme of water at 79°·25, the two kilogrammes of water produced possess a temperature of 0°. The knowledge of this result permits the determination of the specific heat of a body by ascertaining experimentally the weight of the ice which can be melted by lowering its own temperature to 0°. The following is the process:—

A cavity is made in a compact and homogeneous block of ice, the sides of which are carefully dried; a piece of the substance, the temperature of which is above 0°, whose specific heat is sought, is then introduced; a thick plate of ice is then placed over the cavity, to which it serves as a covering (Fig. 322). During the act of cooling, the substance melts a portion of the ice with which it is in contact, and the resulting water is collected and weighed. Let us suppose that the result is 100 grammes of water, it is evident that the heat disengaged by the body during its cooling to 0°, has been the tenth part of 79·25 calories or 7·925 calories. By hypothesis the body weighed 2 kilogrammes, and was at first at the temperature of 35°; then dividing 7·925 by 35, and afterwards by 2, the quantity of heat disengaged by 1 kilogramme for a variation of 1° will be found; that is to say, the specific heat of the body. In the particular case we have chosen it would be 0·113, the specific heat of iron.

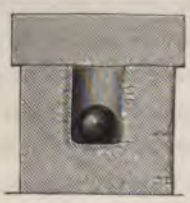
FIG. 322.—Measure of the specific heat of bodies. Simple ice calorimeter.

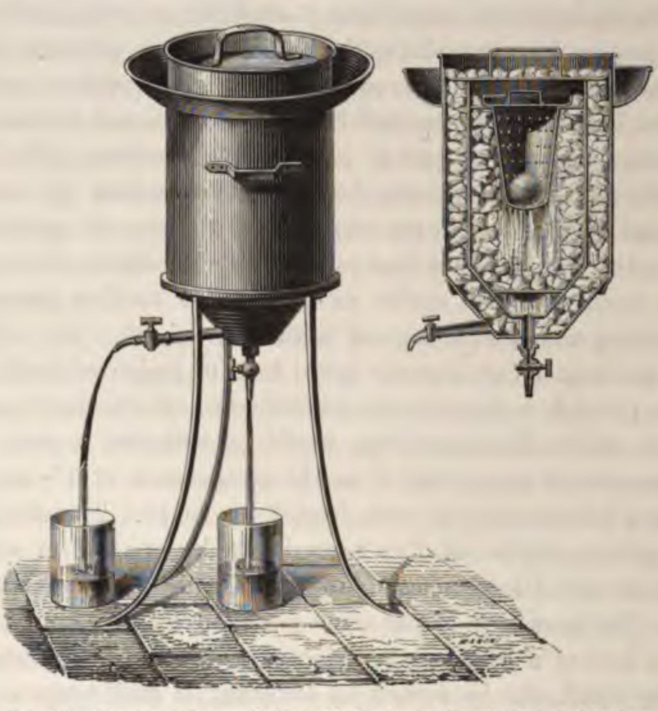
FIG. 323.—Measure of the specific heat of bodies by the ice calorimeter of Laplace and Lavoisier.

Instead of ice cavities, the ice calorimeter invented by Laplace and Lavoisier may be preferably employed. Fig. 323 represents it in section and elevation. It is an instrument formed of three vessels, which are placed one within the other, while the spaces between them are filled with pounded ice. The heated body is placed in the smallest vessel; during cooling it melts a certain amount of ice, and the water is collected by a stopcock at the bottom of the vessel. The ice between the two outer vessels prevents the fusion, by external heat, of that which is in contact with the heated body.

These methods do not give very exact results; if we have preferred them to more perfect methods, it is because our aim is principally to explain the possibility of measuring quantities of heat. Those who desire to extend their knowledge on this subject must have recourse to special works, among which we may mention the beautiful Memoirs of M. Regnault on the specific heats of vapours and gases.

A kilogramme of water, at the boiling-point, or 100°, requires 536 calories in order to convert it into steam. During the condensation of the steam thus formed, it will disengage the same quantity of heat; the application of steam to the warming of buildings is based on this fact. In the arts, the latent heat of steam is also employed to raise the temperature of large masses of liquid.

CHAPTER VII.

SOURCES OF HEAT.

Solar heat: measure of its intensity at the surface of the earth, and at the limits of the atmosphere; total heat radiated by the sun—Temperature of space—Internal heat of the globe—Heat disengaged by chemical combinations; combustion—Heat of combustion of various simple bodies—Production of high temperatures by the use of the oxyhydrogen blowpipe—Generation of heat by mechanical means: friction, percussion, compression.

IT follows from our foregoing study of calorific phenomena, that two or more bodies when in the presence of each other make a mutual and continuous exchange of heat, either by radiation at a distance, or by conduction. From this point of view, a piece of ice at 0° C. is a source of heat to a body which is at a lower temperature than its own.

However, in general language, this expression "source of heat," or "heat-source," is more particularly reserved for bodies which possess high temperatures, and which emit in a continuous manner a certain quantity of heat for a limited or even for an apparently indefinite time. Incandescent solids and gases, fire and flame, are sources of heat according to this view: in the same category may be placed bodies which emit obscure heat at a high temperature, for instance boiling water.

Lastly, the expression "source of heat" is also given to the different modes of production of heat: in this sense, friction, percussion, electricity, and combustion—that is to say, certain physical or chemical actions—are sources of heat. The heat which organized and living bodies emit, is of the same order.

Sometimes sources of heat are classed as temporary and accidental, natural and artificial, cosmical and terrestrial; but these distinctions, which are not based on the nature of the heat-sources, teach us nothing more than that there may be a particular study of each kind. We will therefore review them one after the other, beginning with the sun, the most important of all,—at least to the earth.

The appearance presented to us by the sun is probably due to an enormous layer of cloud built up of solid or liquid incandescent particles, the layer being surrounded by an absorbing gaseous atmosphere; as is proved by the analysis of the solar spectrum. The opinions of men of science are divided as to the nature of the nucleus: some regard it as an incandescent solid or liquid, others as a gaseous mass likewise incandescent. We know nothing of the way in which the immense amount of light and heat is renewed and maintained: it radiates in every direction into space, and its intensity does not appear to have sensibly varied for thousands of years.

The intensity of the solar heat, as it reaches the surface of the earth, has been calculated by Sir J. Herschel at the Cape of Good Hope, and M. Pouillet in Paris. The instrument used by the latter for this determination, which he called the *pyrheliometer*, is represented in Fig. 324. At the upper part we notice a very thin silver cylindrical vessel, the face of which is turned towards the sun and is covered with lamp-black; this vessel is filled with water, and the temperature of the liquid is indicated by a thermometer whose bulb is immersed in the interior of the cylinder, and whose tube is protected by a brass tube pierced longitudinally with a groove so that the level of the mercury can be seen. At the other end of the tube is a disc of the same diameter as the cylindrical vessel, which receives the shadow of the latter, and indicates whether the blackened surface is exposed normally to the direction of the sun's rays: this is the case when the lower disc is exactly covered by the circular shadow of the upper one. The temperature of the instrument is first noted; its blackened face is then exposed to a portion of the sky without clouds, but in such a manner that it does not receive the solar rays: at the end of five minutes its radiation has produced a certain lowering of temperature. The instrument is then directed towards the sun; the blackened face receives the solar heat falling perpendicularly upon it for another five minutes. The elevation of temperature is now noted, and the instrument is again caused to radiate its heat for five minutes in its first position; the final cooling must then be observed. The first and third observations are necessary for the calculation of the quantity of heat lost by radiation by the instrument during its exposure to the sun,—this quantity being a mean between the two observed coolings. By adding to it the heating due to direct exposure to the sun, the total elevation of temperature will be obtained; and consequently the number of calories can be calculated which have been absorbed during a minute by a surface equal to that of the blackened disc.

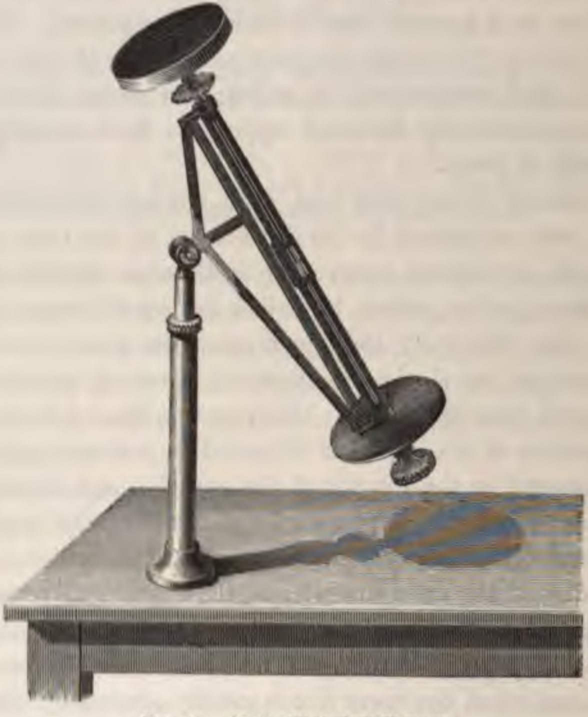

FIG. 324.—M. Pouillet's Pyrheliometer.

This quantity of heat depends, as a matter of course, on the elevation of the sun above the horizon; for before reaching the surface of the earth, the heat-rays of the sun traverse the atmospheric strata, which absorb a certain proportion increasing with their thickness. M. Pouillet has studied the law which regulates the calorific intensity of the sun according as its height varies, and he has determined the absorption due to the atmosphere if the sun were at the zenith. This absorption varies to a certain extent according to the purity of the atmosphere, and may rise to 0·25; that is to say, to one-fourth the amount of heat which would reach the earth if the atmosphere did not exist.

Considering the total heat received by an entire hemisphere, and consequently at every possible degree of obliquity, it is found that the proportion absorbed by the atmosphere is comprised between four and five-tenths of the heat emitted by the sun, if the sky were entirely without clouds. The surface of the earth therefore scarcely receives more than one-half of the solar heat, this being distributed unequally according to the obliquity of the rays; the other half warms the atmosphere.

Supposing the heat received by the earth to be uniformly distributed, M. Pouillet has calculated that a square centimetre receives 0·441 calorie per minute; that is to say, a quantity of heat sufficient to raise the temperature of 441 grammes of water 1°. In one year, each square centimetre receives 231,675 calories: the quantity of heat received in a year by the entire earth, would be sufficient to melt a layer of ice 31 metres in thickness surrounding the globe.

From the quantity of heat received annually by the earth, the total amount of heat radiated by the sun into space can be deduced. This may be done by calculating how many times the surface of a great circle on the earth, *i.e.* an area equal to a section of the earth, is contained in the surface of a sphere which has the centre of the sun for its centre, and the distance from this body to our globe for its radius. An easy calculation gives 2,150,000,000, so that the heat intercepted by the earth is only $\frac{1}{2150000000}$ part of the entire solar radiation. "The heat emitted by the sun," says Tyndall, "if used to melt a stratum of ice applied to the sun's surface, would liquefy the ice at the rate of 2,400 feet an hour; it would boil, per hour, 700,000 millions of cubic miles of ice-cold water. Expressed in another form, the heat given out by the sun per hour is equal to that which would be generated by the combustion of a layer of solid coal ten feet thick, entirely surrounding the sun; hence the heat emitted in a year is equal to that which would be produced by the combustion of a layer of coal seventeen miles in thickness."

Such is the calorific intensity of the immense body which furnishes the earth and the other planets with their supply of heat, and, as we shall presently see, their provision of life and mechanical force. We do not yet know how this prodigious activity is maintained; nevertheless, several ingenious hypotheses have been made concerning it, but which, we must remember, rest solely on conjecture.

The earth also receives heat-rays emitted by the stars, which are heat-sources similar to that of which we have just spoken. At the almost infinite distance of the stars, the heat radiated by them is so feeble as to be almost inappreciable: indeed, it is almost impossible to measure it. Nevertheless some successful attempts have been made, by means of large telescopes which grasp a large number of these radiations, and delicate thermo-electric piles. Thus Mr. Stone has found that the heat received from Arcturus is equal to the radiation of a Leslie cube of boiling water at a distance of 383 yards. The whole of these distant radiations, that of the sun excepted, determines what is called the temperature of space, which has been estimated by many *savants*. According to Fourier, this temperature is – 60° C.; M. Pouillet states that it is much lower, and can scarcely exceed – 140° C.

The surface of the earth also receives heat from its interior—heat which belongs to the terrestrial globe itself, as Fourier has proved. At a certain depth below the surface, a stratum is found with a constant temperature which is nearly the mean temperature of the place.

Below this stratum the temperature increases, and its mean augmentation is about 1° for 30 metres. If this increase of heat, which has been proved to a depth exceeding 700 metres, continues in the lower strata and in the same proportion; at 3 kilometres the temperature would already reach the boiling-point, and at 40 kilometres most of the known minerals would have attained their melting points. But it remains to be proved whether the enormous pressure to which the terrestrial strata are subjected at this latter depth, is not an obstacle to their liquefaction: the incandescence of the terrestrial nucleus thus remains in an hypothetical state.

The sun is the most abundant and economic source of heat: but it is not the most convenient, because we cannot adapt it at will to our purposes, and, when it is clouded over, or is invisible, we most require heat: nor is it the most intense, for unless it is concentrated by means of expensive apparatus, it only produces comparatively low temperatures. It may be safely affirmed that civilization would be an impossibility if man had only the solar heat at his command, and had not discovered artificial sources of heat to satisfy the most indispensable wants of his existence. Combustion, that is to say, the chemical combination of certain bodies with oxygen, constitutes one principal source of this kind, and the term artificial heat-sources is applied to those which can be used at will, and the intensity of which can be regulated according to the wants of the moment.

Generally speaking, whenever substances enter into combination, heat is disengaged. Thus, a mixture of water and sulphuric acid, and of water and a certain quantity of quicklime, is accompanied by a considerable rise of temperature.

The combination of oxygen, one of the constituents of our atmosphere, with certain solid or gaseous elements, gives rise to a very intense disengagement of heat accompanied by light, and frequently produces the phenomenon of vivid combustion. But in order that a combustible body may burn, either in the air or in pure oxygen, one of its parts must first be brought to a high temperature; in fact, it must be lighted. When once the combination has commenced, the heat disengaged by it is communicated in succession until the combustible gas is entirely extinguished, or the body with which it is combined is completely consumed. It is thus that we obtain fire in our stoves and the light of our candles and lamps; and we know by experience that these sources of heat and light only last so long as they are kept up,—that is to say, while they are furnished with the two elements necessary for the combustion.

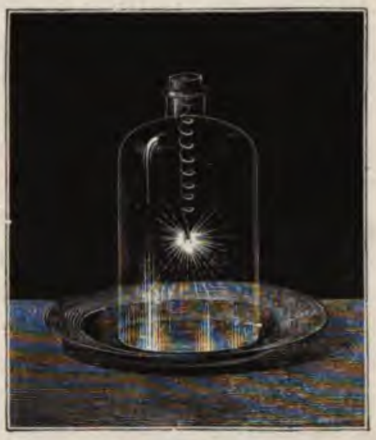

FIG. 325.—Combustion of iron in oxygen.

When combustion takes place in pure oxygen, it is much brighter than in air. On plunging a steel spiral furnished with a piece of burning tinder into a bell jar filled with this gas (Fig. 325), a very bright combustion of the metal is produced, and it sends out a number of sparks in every direction.

The phenomenon of combustion is complex, but we cannot here analyse it in all its details: we will only say that the flame proper must be distinguished from the solid incandescent portions. In order that a body may burn with a flame, there must be a disengagement of certain gases under the influence of a high temperature; and these gases in becoming luminous produce the moveable light of which we speak. In the flame of a candle or jet of gas there are three distinct portions in which the heat and light are associated in different proportions.

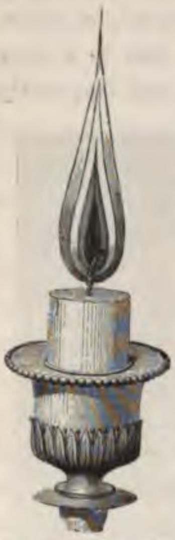
FIG. 326.—Flame of a candle.

The exterior layer is the seat of the most active combustion and of the highest temperature,[1] but the light of this region is not intense; next comes a very luminous stratum where the combustion is always less complete, and the heat less intense, but which shows great brilliancy: whether this is on account of the very fine particles of incandescent carbon of which it consists, or on açcount of the density of the vapours, is not yet decided. Lastly, at the interior of the flame, there is a dark space, possessing a much lower temperature, because, as the oxygen of the air cannot penetrate to it, the gaseous matters which fill it are not burnt. It is only on reaching the top of the flame that these matters are burnt in their turn: when the combustion is incomplete, they rise in the form of smoke.

If the flame of a candle is blown upon quickly, we all know what happens,—the light is extinguished; and the reason of this fact is simple: by the act of blowing, cold air is introduced into the inflammable gas, which cools on being diffused into a quantity of air; the temperature then falls to such an extent that combustion ceases. If, after having blown out the flame, the wick remains incandescent, by blowing it lightly it is again lighted, because the oxygen necessary for the combustion is introduced, and the gas again disengages itself, and is inflamed at the point of contact of the solid incandescent parts.

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[1] A spectroscopic examination of a candle-flame affords a very beautiful proof that the exterior part of the flame is the hottest, for this region gives us the bright line of sodium, which would be a dark line, when the spectroscope is directed to the brighter part of the flame, if this were not so.

Several physicists—among others, Laplace, Lavoisier, Rumford, Despretz, Dulong, Fabre, and Silbermann[1]—have endeavoured to measure the quantities of heat which are disengaged during chemical combinations, and especially during ordinary combustion. The number of calories which are disengaged when a unit of weight of a combustible body is burned, is what is called the *heat of combustion* of that body. We cannot describe the methods which have been employed in these important researches, and shall only give some results which show to how great an extent the elements differ in this respect. Whilst the heat of combustion of 1 gramme of native sulphur is 2,260 calories (the calorie is in this case the quantity of heat necessary to raise 1 gramme of water 1° C.), that of 1 gramme of carbon in the state of diamond is 7,770 calories; the same body in the state of natural graphite is 7,796; and lastly, as charcoal, 8,080 calories. Hydrogen burning in chlorine disengages 23,783 calories, and the same gas burning in oxygen 34,462.

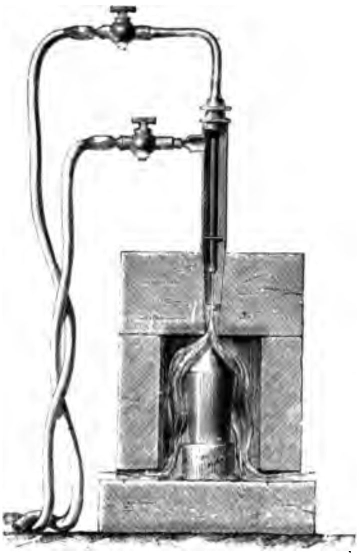

FIG. 327.—Oxyhydrogen blowpipe.

The heat of combustion of hydrogen is the most intense of all; it has been calculated that it corresponds to an elevation of temperature of 6,800°; which has led to the employment of this extreme heat for the production of extremely high temperatures. MM. H. Sainte-Claire-Deville and Debray, by using the oxyhydrogen blowpipe, have fused considerable masses of platinum; a kilogramme of this metal requires for its fusion, and for keeping it in a state of fusion during the time of refining, a consumption of 70 litres of oxygen and 120 litres of hydrogen.

Mechanical action, friction, percussion, and compression, develop n, just like the more intimate motions which constitute the phenomena of chemical combinations. There are numberless examples of this transformation of motion into heat, and we can each observe them for himself. We will mention some of them.

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[1] Andrews of Belfast has made *very* accurate experiments on this subject.

When a metal button is quickly rubbed against cloth or any solid body, it becomes warm, and finally very hot: schoolboys well under- d this experiment. The friction of a saw against the piece of od which it is dividing, that of a razor or knife which is being ground, of a file against the metals which it wears away, raises the temperature of the objects subjected to these violent motions, the molecules of which are thus disturbed. The sparks produced by horses' shoes on the pavement, or by the friction of the steel on the wheel of a grindstone, or again, those which set light to tinder in the int and steel method, all proceed from the high temperature produced by friction; very fine metallic particles are detached, and the heat developed is sufficient to set the little masses on fire.[1]

V of wood rubbed against each other become heated, is engaged, and, if we may believe the stories of rave es by these means procure fire. Turners sometimes pro hands on the objects which they are making by od against the spot which they wish to char. from this pressure, joined to the rapid rotatory movement of the lathe, is strong enough to carbonize the wood on the circumference of the object. The pivots of machines, the axles of carriages and railway carriages, become strongly heated by the friction which results from a rapid and prolonged rotation; indeed they would take fire, or get red-hot, if care were not taken to lubricate or grease them.

We may quote here, as an example of the enormous quantity of heat which can be disengaged by the friction of two solids against each other, the celebrated experiment made by Rumford in 1798; this experiment had been suggested to that celebrated physicist, whilst he was superintending the boring of some pieces of cannon at Munich.

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[1] "Before the discovery of Davy's safety lamp, the fire-damp was the great trouble of mines; and many mines remained unexplored and inaccessible on account of the presence of this invincible enemy. As common lamps could not be used, the passages were illuminated by means of a steel wheel which was caused to turn against a gun-flint."—SIMONIN, *La Vie Souterraine.*

Struck by the great quantity of heat disengaged during this operation, he wished to measure it as exactly as possible; accordingly he placed a metal cylinder, destined for the operation of boring, in a wooden case filled with water, the temperature of which was shown by an immersed thermometer. An hour after the friction of the blunt borer against the cylinder had commenced, the temperature of the water, at first 16°, rose to 46°. At the end of two hours, it was 81°, and again, half-an-hour later, the water completely boiled. "It would be difficult," said Rumford, to describe the surprise and astonishment expressed in the faces of the assistants at the sight of such a quantity of water (about ten litres) heated and caused to boil without any fire."

The friction of solids against liquids and gases also develops heat. Joule's experiment, to which we shall presently refer, proved the heating of a liquid when agitated by metallic paddles turning on an axis in it. The incandescence of aërolites is by some attributed to friction against the atmosphere, which they enter with considerable velocity. The elevation of temperature caused by the friction of a gas against a solid is placed beyond doubt by a very simple experiment made by Tyndall in his Lectures on Heat: by means of a pair of bellows he caused a current of air to impinge on one of the faces of a thermo-electric pile; the needle of the galvanometer was immediately deviated, and the direction of the deviation indicated that the face of the pile had been heated by the moving air.

We will end this enumeration of phenomena which prove the generation of heat by mechanical force, by quoting an important experiment of Davy's. This illustrious physicist, by rubbing two pieces of well-dried ice together, succeeded in melting a certain quantity. Now, to explain the disengagement of heat produced by friction, the partisans of the material theory of heat, who considered it a fluid contained in the interstices of bodies, reasoned thus: Friction changes the calorific capacity of different bodies; it diminishes this capacity so that the heat which was retained before the mechanical actions can no longer remain within the body after the molecular change which agitates it: it is this heat which is disengaged by friction, and, before latent, now becomes apparent."

The experiment of Davy renders this explanation impossible; let us bear in mind that water has double the calorific capacity of ice;

after the fusion of a certain quantity of ice, the water produced by it contains more latent heat than before: hence it would be impossible to understand, in accordance with the material theory, whence the heat proceeds which has caused the ice to pass into water. From this it is concluded that the mechanical force brought into play in friction is transformed into heat,—that is to say, into a force of another kind: that there is transformation of visible motion into molecular or atomic motion.

Percussion and compression develop heat like friction. Thus, when a nail is driven into a piece of wood with a hammer, not only is the nail heated, an effect which could result partly from the friction against the wood, but the hammer itself undergoes an elevation of temperature. An iron bar, beaten with successive strokes, can be made red-hot. Plates of gold, silver, and copper, compressed under the coining press which is used to stamp money, become heated, but the elevation of temperature is not the same in different metals. Generally speaking, the quantity of heat developed by mechanical action depends on the nature of the substances submitted to these actions, on the state of their surface, and on the pressure exercised.

The compressibility of liquids is very slight: nevertheless, by submitting liquids to considerable pressure—for example, of from 30 to 40 atmospheres—the disengagement of heat can be established. The compression of gases can be effected to very extensive limits: and a considerable elevation of temperature can be obtained, when a gaseous mass is suddenly compressed into a limited space. This fact shows us the principle of the pneumatic syringe which we have described in the First Book of this work. The expansion of a gas produces an effect contrary to that of compression,—that is to say, a fall of temperature results; carbonic acid gas, first liquefied by compression under 40 or 50 atmospheres in a receiver, produces so much cold by expansion on escaping into the air that it passes into the solid state; and then takes the form of flakes, white as snow, of solidified carbonic acid. Their temperature is then 93 degrees below zero Centigrade.

The same phenomenon of cooling takes place, when steam issues in a jet from the valve of Papin's digester. Its sudden expansion is accompanied by a cooling which condenses it as mist: on plunging the hand into the jet of steam, a sensation of coolness is felt which at first seems strange. Great care must be taken in this experiment when the vapour contained in the boiler has only the ordinary atmospheric pressure; on escaping into the atmosphere, at this pressure, it retains the temperature of 100° C., and the hand may be terribly scalded.

In order to complete what we have said concerning heat-sources, we have yet to mention those which life maintains in organized beings, vegetable and animal. It seems to be proved that animal and vegetable heat has its origin in a series of chemical actions more or less complex, which constitute the phenomenon of nutrition, respiration, and assimilation of food.

CHAPTER VIII.

HEAT A SPECIES OF MOTION.

What we understand by the mechanical equivalent of heat—Joule's experiments for determining this equivalent—Reciprocal transformation of heat into mechanical force, and of mechanical force into heat—Heat is a particular kind of motion.

IN the study of the science of heat, we have considered two classes of phenomena. On the one hand, we have described the many effects produced by the variations of heat in bodies; and, on the other, we have reviewed the different processes by which heat can be engendered. We have now to indicate the relations which exist between these two orders of phenomena, the reciprocal dependence of which, being now proved, constitutes the mechanical theory of heat.

We have seen that one of the effects of heat is to expand bodies, that is to say, to produce molecular movements which increase the distances of the molecules from each other; and, thus considered, expansion is nothing more than a mechanical effect. When the increase of heat attains a certain limit, there is a change of state, a passage from the solid to the liquid condition, and from the liquid to the gaseous condition: this is also a mechanical effect, for it does not appear doubtful that these modifications in the aspect of a substance are due to variations in the respective distances of the molecules, and afterwards in the actions which they exercise on each other. We have also seen that increase of heat confers on vapours and gases the elastic force which, in modern machines, so advantageously replaces the old motive forces. In all these cases, heat is transformed into mechanical work; or, in other words, a certain quantity of heat is consumed in producing *work*, although in many cases this work is not susceptible of measurement in the present state of science.

It is not less evident, however, that whenever heat is produced, a certain quantity of work is expended; this is most certain in the case of heat engendered by friction, percussion, and compression: that which is disengaged by chemical action is believed to be produced by the molecular movements which constitute the combinations.

This relation between the forces which give rise to the phenomena of heat and the other mechanical forces, had been suspected for some time: but it was reserved to our time to transfer it from a state of vague hypothesis to that of a theory proved and verified by experiment. Dr. Mayer, of Heilbronn, a little town in Germany, had the honour of giving the first definite formula to the theory and of developing the consequences: in 1842 he calculated the mechanical equivalent of heat, which was experimentally determined a year later by an English physicist, Dr. Joule, who was at that time unacquainted with the researches of the German doctor.

Many other physicists may be referred to as having aided to establish this important theory; it will be sufficient for us to mention MM. Regnault and Hirn in France, Clausius in Germany, Thomson and Rankine in England.

We will now endeavour to give an idea of the *mechanical equivalent of heat*, and of some of the experiments by which it has been determined.

Let us first recall to mind the meaning of the term *work* in mechanics. When a power is employed in a machine in motion to overcome a resistance with which it is in equilibrium, it has been proved that there is always an equality between the products obtained, by multiplying, on the one hand, the power by the path passed over, by its point of application; and, on the other hand, the resistance by the path over which the point of application of this latter passes. For example, if a power equal to 10 kilogrammes produces equilibrium with a resistance of 30 kilgrammes, and the path traversed by this according to its direction be 1 metre, the path traversed by the power during the same time will be 3 metres; there will then be equality between the two products 10 × 3 and 30 × 1.

The name of *work* is given to each of these products; the first is *work spent on the machine*, and the second *work done by the machine*. It is convenient to take as a unit of work or dynamic unit, the work developed by raising a weight of 1 kilogramme to a height of 1 metre. This unit is designated a *kilogrammetre*. On the other hand, we have seen that quantities of heat are measured in calories; by calorie is understood the heat necessary to raise from 0° to 1° Centigrade the temperature of 1 kilogramme of water. The problem which presented itself to physicists was: To determine by experiment and calculation the number of kilogrammetres necessary to engender the quantity of heat represented by a calorie. (English men of science use a different unit, called a foot-pound.)

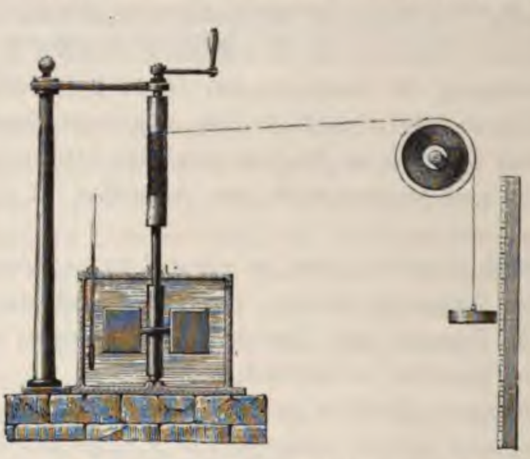

FIG. 328.—Joule's experiment. Determination of the mechanical equivalent of heat.

We deal first with the heat which raises 1 kilogramme of water 1° C., and then determine the mechanical work necessary to produce the same result.

It is this number which Mayer has called the *mechanical equivalent of heat*. The various experiments which have been made with a view of determining this important number, consist essentially in the production of a certain quantity of heat by the aid of mechanical action, and in measuring carefully the heat produced, and the work consumed in the operation, of course taking into account losses of heat and of mechanical work. The following are some of Joule's experiments.

He compressed air, by means of a force-pump, into a metallic vessel in the water of a calorimeter. After a certain number of strokes of the piston, the pressure of air having attained a certain number of atmospheres, he observed the elevation of temperature of the water, and deduced from it the quantity of heat communicated to it. The heating was not entirely due to the compression of air, but also to the friction of the piston. He therefore recommenced the operation by allowing the receiver to communicate with the atmosphere, that is to say without compressing the air. The heat produced by this fresh operation was evidently due to the friction in the first operation. Joule found by this method 444 kilogrammetres for the mechanical equivalent of the heat.

By turning a paddlewheel in water or in mercury (Fig. 328), the same physicist observed the elevation of temperature of the liquid, and likewise deduced the number of calories caused by the friction. On the other hand, he easily measured the work expended in producing the rotation. The final result arrived at by Dr. Joule gives, as the mechanical equivalent of heat, 772 foot-pounds; that is, the force expended in raising 1 lb. through 772 feet will raise the temperature of the pound of water 1° F.

To sum up, it has been shown by a great number of experiments made by various physicists, that the mechanical equivalent of the heat necessary to raise 1 kilogramme of water 1° C. is about 425 kilogrammetres. Or, according to the definition given above, that the quantity of heat necessary to raise the temperature of a kilogramme of water 1° C. is capable, if it could be entirely expended in mechanical work, of raising a weight of 425 kilogrammes to a height of 1 metre. Reciprocally, when work equal to 425 kilogrammetres is completely transformed into heat, the heat produced is capable of raising the temperature of a kilogramme of water 1° C. Thus the transformation of mechanical force into heat and of heat into mechanical force, is not only a fact acquired by science, but an important demonstration which throws light on the nature of the cause to which we must attribute the phenomena which we have studied in this Fourth Book.

The study of the laws of radiant heat had already induced us to assimilate heat-waves with luminous waves, and to regard heat itself as produced by certain vibrations of the ether. On penetrating the interior of bodies it is probable that the heat communicates to their molecules certain movements which, transformed in different ways, sometimes change the volume of the bodies, sometimes modify their physical condition, and sometimes produce intimate effects of such a nature as to change the mode of association of the elementary atoms. These movements, indeed, on being propagated by our nerves, produce in us the sensation of heat.

BOOK V.

MAGNETISM.

BOOK V.

MAGNETISM.

CHAPTER I.

MAGNETS.

Phenomena of magnetic attraction and repulsion—Natural and artificial magnets; magnetic substances—Poles and neutral line in magnets—Action of magnets on magnetic substances; action of magnets on magnets—Law of magnetic attraction and repulsion—Direction of the magnetic needle; declination and inclination; influence of the terrestrial magnet—Process of magnetization—Attractive force of magnets.

MINERALOGISTS gave the name of magnetic oxide of iron, or magnetic iron, to an ore of this metal, which is found in large quantities in the mines of Europe and America, particularly in Sweden, in the Isle of Elba, and in the United States. It was worked for some time at Bone (Algeria); and lastly, according to ancient writers, it was formerly found in Asia Minor, near the two towns of the same name of Magnesia. The mineral to which we refer is composed of protoxide and sesquioxide of iron; its colour is generally black or brown, and sometimes greyish, with a metallic brightness. Some specimens possess the property, known to the ancients, of attracting pieces of iron which are placed near one of their points: these are *natural magnets*, or, as they are more commonly called, *lode-stones.* We shall presently see how the attractive power of the natural magnet can be communicated to tempered steel: the pieces or bars of steel thus prepared are called *artificial magnets.*

Iron is not the only substance capable of being attracted by a magnet: the same effect takes place with other metals: cobalt, nickel, chromium and manganese, cast iron, steel, and all specimens of oxidized iron, which are not themselves magnets, are also attracted. These bodies are ranged under the same head of *magnetic substances*.[1]

The phenomena which we are about to describe remained unknown for centuries like those of electricity; yet the ancients were aware of the two principal facts which, in the hands of modern observers, have been the starting-points of the two branches of physics which are now united. The attraction of light bodies by yellow amber, and the attraction of iron by the lode-stone, were only amusements in [illegible] [illegible] or singularities of nature; in the present day they are, amongst thousands of others, two particular manifestations of an agent universally diffused through, and continually in action in, the physical world.

The attractive power of magnets, natural or artificial, for magnetic substances is easily proved. The following are some of the processes used for this purpose:—

If a magnet is immersed in a quantity of iron filings, we observe on withdrawing it that at certain parts of its surface numerous particles of the metal are attached in the form of tufts (Fig. 329), and on placing small pieces of iron, such as nails, near the same points, they will be seen to move forward to the magnet, and to adhere with a force the strength of which can be determined by the effort necessary to remove them. By means of the magnetic pendulum, which consists of an iron ball or any other magnetic substance suspended

[illegible] Attraction of iron filings by a natural or artificial magnet.

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[1] The etymology of the words magnetism and magnetic is one of the Greek names of the magnet, μαγνήτης, which the ancients themselves believed to be derived from the names of the two towns of Magnesia, in the neighbourhood of which lode-stones were first found. Aristotle called the magnet simply λίθος, the stone, *par excellence*. It was also termed *Lydian* stone, *Hercules* stone—ἡράκλεια λίθος. According to M. Th. H. Martin, this last term was wrongly interpreted as synonymous with the Heraclea stone, one of the names of the town of Magnesia, which induced the ancients themselves to give the name of μαγνήτης to the magnet; which name the Romans retained.

by a thread, the attraction which the magnet exercises on this substance is even more easily proved. The same apparatus also shows that the attraction, which is *nil* at the points where the iron filings are not attached, is at a maximum where the largest tufts have been formed. Moreover, the attraction of magnets for magnetic substances is reciprocal. Thus, a piece of iron brought near a magnetized bar rendered moveable by being suspended, as represented in Fig. 331, attracts the bar, and causes it to move round the axis of suspension.

This last experiment also proves that magnetic attraction is exercised at a distance, and increases in intensity as the distance diminishes; we shall see further on in accordance with what law this takes place. But at the same distances this action is scarcely weakened by the interposition of bodies, either liquid or solid, provided they are not magnetic. Thus when a magnet is moved beneath a sheet of paper, or cardboard, a plate of glass, wood, or porcelain, pieces of iron placed on the surface of these sheets or plates will follow the motion of the magnet.

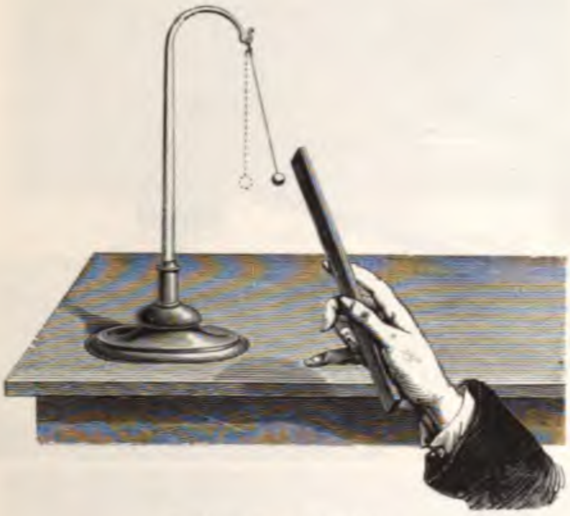

FIG. 330.—Magnetic pendulum.

Although magnets, either natural or artificial, and magnetic substances, are reciprocally attracted, this does not prove that the properties of both are alike. There is an important difference, which we must observe, viz. that substances which are simply magnetic do not attract each other: a piece of iron which attracts a magnet has no action on iron, if it is not in the vicinity of a magnet. There is again another difference on which we shall enlarge, viz. that a piece of iron undergoes attraction at all points, whilst in a magnet the attractive property is unequally distributed: we have already seen that it does not exist at certain points and is at maximum at others. The experiments which follow will show this characteristic difference between magnetic substances and magnets.

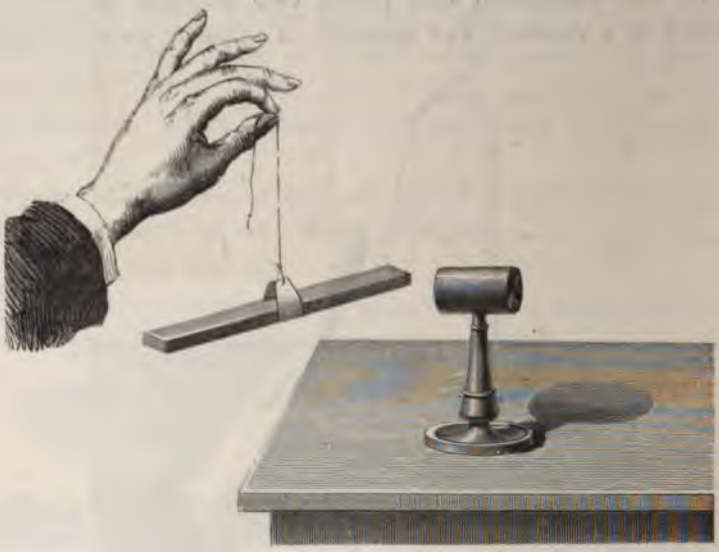

FIG. 331.—Attraction of a magnetic bar by iron.

By examining a magnet which has been placed in iron filings (Fig. 329), the latter are seen not only to be attached more particularly to the two opposite parts, but, moreover, the arrangement of the particles takes a special direction, as if in each part where the attraction is strongest there is a centre of attraction. Towards the middle of the bar, on the contrary, a part will be noticed where no particle of iron has attached itself. The two extreme points of the magnet are called the *poles,* and the middle section of the magnet the *neutral line* or *equator.* The following is an experiment which shows in a still more striking manner the existence of the poles and the neutral line:—On the bar which serves as a magnet a sheet of cardboard is placed, upon which very fine iron filings have been sifted. The particles are now seen to dispose themselves in a regular manner round the poles of the magnet, and to form lines which are convergent and symmetrical with respect to the neutral line *m m′* (Fig. 332). Sometimes a magnet possesses more than two poles: besides the extreme poles, the existence of which we have proved, intermediate points are observed to which the iron filings attach themselves, and which are also separated from each other by neutral lines, as is shown in the magnetic figures represented in Fig. 333. These are called *consequent poles*. It is easy now to explain the difference which exists between magnets and magnetic substances. The latter have neither poles nor neutral lines: whichever of their points is presented to the poles of a magnet there

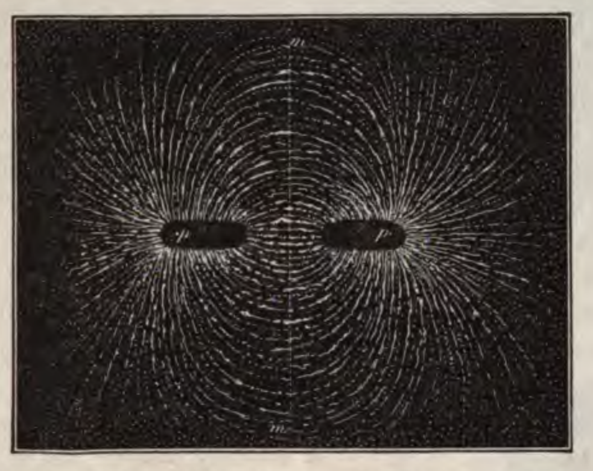

FIG. 332.—Magnetic figures. Distribution of iron filings on a surface.

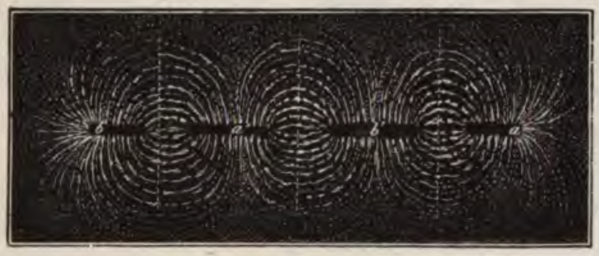

FIG. 333.—Consequent points, or secondary poles of magnets.

magnet comports itself in the presence of the bar, or of a piece of lodestone. If there is attraction at every point, it is not a magnet; but if there is attraction at one extremity and repulsion at the other, it is a magnet, not simply a magnetic substance.

Magnetization is the condition of a substance which has the property of attracting iron and other magnetic bodies, and which substance possesses two poles and a neutral line. This property may be permanent or temporary: it is permanent in natural magnets or steel bars magnetized by processes of which we shall soon speak. The following experiment proves that it is temporary in magnetic substances which are in contact with one of the poles of the magnet:—

A small cylinder of soft iron can be raised by means of a magnet; this is magnetized by the influence of the magnet, for on approaching a second cylinder of iron to its extremity, it undergoes an attraction and is also raised. Thus what is called a magnetic chain can be formed at the end of the bar, composed of pieces of iron which attract and support each other. But if the magnet in contact with the first piece of soft iron is removed, in an instant all the others fall, thus losing the temporary magnetism with which the presence of the magnet had endowed them. Each piece of soft iron becomes for the time being a magnet with two poles and a neutral line, and this is proved by the fact that if magnetic figures are formed during the contact of the magnet and the iron cylinder, the iron filings arrange themselves in a manner which corresponds to that of the magnet itself. It will also be noticed that the neutral line is nearer the pole next to the magnet than to that which is more remote. Magnetic attraction does not require absolute contact; it is only necessary that the distance be sufficiently small between

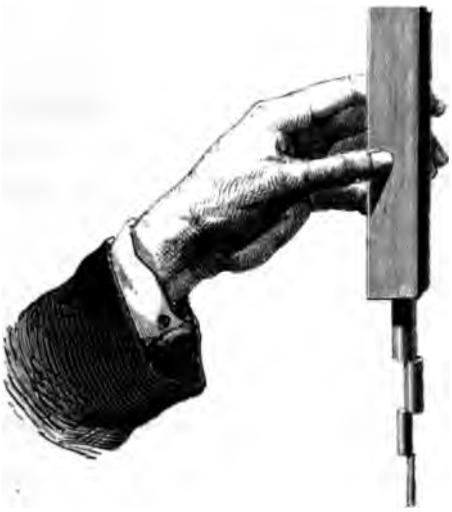

FIG. 335.—Magnetization by the influence of magnetism.

the pole of the magnet and the piece of soft iron which momentarily acquires the polar magnetism, and this distance depends on the strength of the magnet employed.

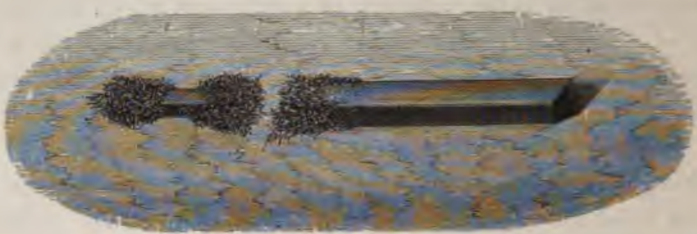

FIG. 336.—Magnetization by influence at a distance.

When a magnetic bar is broken into two or more pieces, each piece, however small it may be, becomes a complete magnet with two poles and a neutral line; only, its magnetic power is no longer so strong as in the first magnet, as may be proved by the weights of soft iron which each is competent to lift. The magnets which proceed from this rupture have their poles of contrary names end to end; that is to say, situated at the two extremities of the pieces near each other which were joined before the rupture, as in Fig. 337.

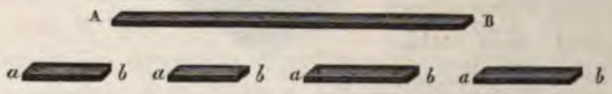

FIG. 337.—Rupture of a magnet; disposition of the poles in the pieces.

A magnetic needle is a lozenge-shaped piece of steel endowed with the property of a common magnet; that is to say, having a pole at each extremity and a neutral line at its centre. A magnet of this kind suspended horizontally in a loop of paper by an untwisted, thread of silk, or well mounted on a pivot with an agate centre (Fig. 338) in such a way that it can turn freely in every direction, after some oscillations always assumes a certain direction in a horizontal plane; at least, it undergoes variations of but slight amplitude.

This property of the magnetic needle to turn one of its poles towards the northern horizon, has been utilized for centuries by navigators.[1]

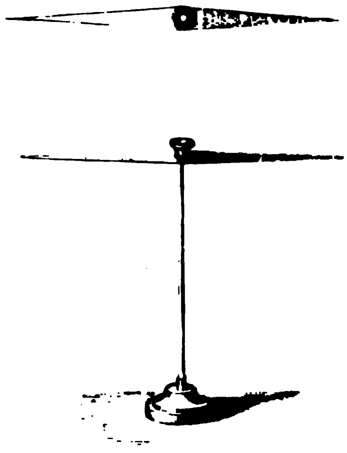

FIG. 338.—Magnetic needle.

It is not always, however, that the needle turns to the true North, so that the vertical plane passing through its poles does not coincide with the meridian plane of the place. The angle of the two planes is called the *declination* of the magnetic needle, or, simply, declination. We shall see, when speaking of terrestrial magnetism, that the declination is not the same in every part of the world; in some places it is *nil*, in other regions it is to the east and in some to the west: moreover, in the same place, it varies in the course of centuries. At the present time, at Paris, the declination is west, and about 18° 30′, that is to say, the vertical plane passing through the poles of the magnetic needle—a plane called the magnetic meridian—makes with the geographical meridian plane an angle of 18 degrees and a half. At London this declination is about 21°. One of the poles of the needle is turned nearly to the N.N.W. This constancy of direction, in freely suspended magnets in a horizontal plane, may be simply put to the test by a magnetized sewing needle. On placing it on a cork float on water perfectly at rest, the needle assumes the direction of which we have just spoken. Moreover, between the two poles of the needle, there is a very characteristic difference; for if, when the needle is in equilibrium, it is turned end for end, it does not keep its new position, when even the direction which has been given to it is identical with the first; it will be seen to turn on itself, describe a semi-circle, and again assume its original position, so that the same pole is always turned to the north.

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[1] It appears certain that from the second century before the Christian era, the Chinese used compasses indicating the direction of the South. These compasses carried a little statuette, which turned on a vertical point, the extended arm of which always pointed to the South, because it contained a magnetic needle, whose south pole was towards the hand and the north pole towards the elbow. (Th. H Martin.) The compass with a balanced needle was known to the Arabs, who doubtless transmitted it to Europeans about the twelfth century.

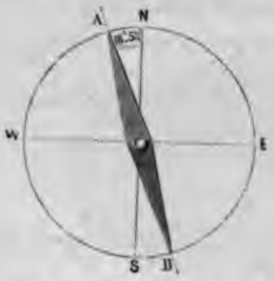


FIG. 339.—Magnetic declination in Paris, October 1864.

If instead of placing the magnetic needle so that it can turn freely in a horizontal plane, it is suspended by its centre of gravity round a horizontal axis, it will be able to turn freely in a vertical plane. Let us suppose this plane the magnetic meridian. Then the one of the two poles turned towards the north is inclined, and dips below the horizon, making with this plane an angle which is called the *magnetic inclination.* In some parts of the earth, near the equator, the inclination is *nil;* it increases generally in proportion as the latitude increases, and near the poles there are points at which it is at a right angle: the magnetic needle there assumes a vertical position; these are the *magnetic poles* of the earth. At Paris, the inclination, which varies slightly from year to year, is at the present time about 66°.

A magnetic needle may be arranged so that it places itself in the magnetic meridian, with an inclination to the horizon such as we have just stated. Fig. 341 shows an arrangement which allows the needle to turn on a horizontal axis passing through its centre, and can then take up the local dip as the axis is suspended by a thread. The system begins by oscillating, until the needle is in the magnetic plane, and then it dips to an extent equal to the inclination at the place. Elsewhere we shall have occasion to describe the instruments by which we accurately measure the inclination and declination of the magnetic needle: to these instruments the name of *magnetometers* has been given.

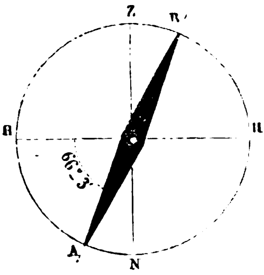
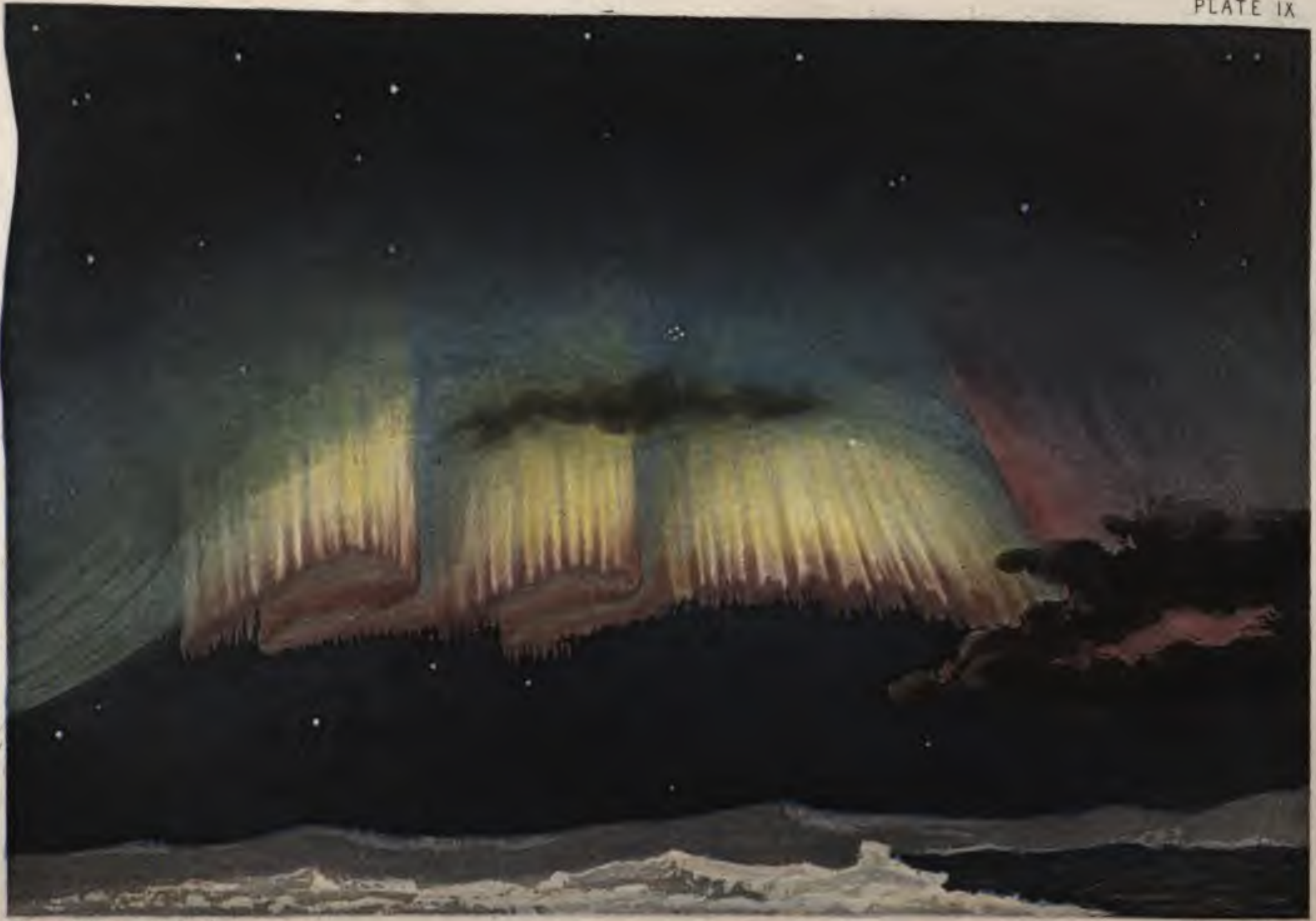


FIG. 340.—Inclination of the needle at Paris, October 1864.

These experiments prove to us that the terrestrial globe exercises an influence on a magnet similar to that which one magnet exercises on another. It is just as if, at the interior of the earth, there existed

PLATE IX



D'après Silbermann & Bévalet

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POLAR AURORA BOREALIS

a powerful magnet possessing two poles. Physicists have stopped at this hypothesis, which, moreover, does not imply the existence of a material mass analogous to the natural magnets, and lying in the deep strata of our spheroid, as we shall see when we study the relations which exist between magnetic and electric phenomena. If the earth is compared to a magnet, the pole in the northern hemisphere will naturally be called the northern magnetic pole, and that in the southern hemisphere the southern magnetic pole. But, from the preceding we have learnt that poles of contrary names attract each other, while those of the same name repel each other; it follows, therefore, that the pole of the magnetic needle which turns to the north is the southern pole of the needle, whilst the pole turned towards the south is its northern pole. When the position of the needle has only to be considered, its southern pole is called the north pole, and its northern pole the south pole. But if the law of the mutual action of the two magnets is well understood, their denominations cannot be equivocal.

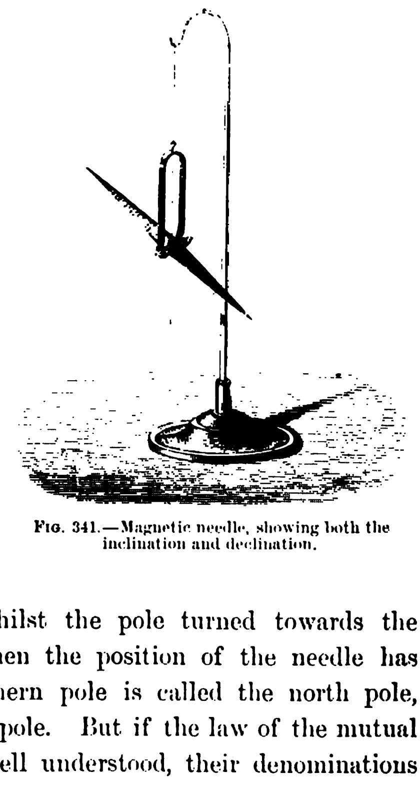

FIG. 341.—Magnetic needle, showing both the inclination and declination.

The inclination and declination of the magnetic needle are subject, in different regions of the globe, to variations, some of which are periodical whilst others appear to be irregular. Sometimes even the needle undergoes perturbation, as if the terrestrial globe was the seat of real magnetic storms; then we see towards the polar regions luminous phenomena, visible at great distances, known as the northern or southern auroras. Plate IX. represents a polar aurora observed in the north of the Scandinavian peninsula. We shall give a description of this phenomenon in Book VII., devoted to atmospheric meteors.

Hitherto we have only spoken of the direction of the actions which magnets exercise on each other, or on magnetic substances. The intensities of the forces of attraction and repulsion which reside in the poles of magnets have also been measured. For this purpose Coulomb used an instrument similar to the torsion balance, which enabled him to measure these forces; this is the magnetic balance represented in Fig. 342.

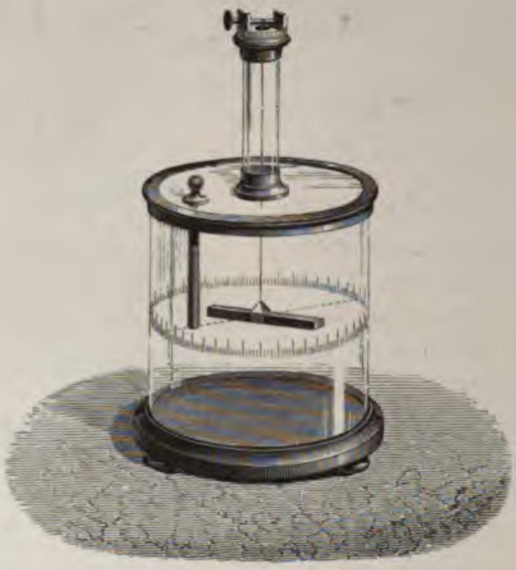

FIG. 342.—Coulomb's magnetic balance.

A long magnetic bar is suspended by a metal thread placed so that it is in the magnetic meridian without any torsion of the thread; if the thread is now turned in such a way as to throw the bar out of this first position, and to cause it to make a certain angle with it, the force of torsion will be equivalent to the intensity of the action of the terrestrial magnetism which tends to bring back the bar into the magnetic meridian. Coulomb commenced by assuring himself that this intensity is proportional to the angle of displacement of the bar, for small deviations. If we then place vertically at the side of the instrument, as shown in the figure, another magnet in the magnetic meridian (shown by the dotted line), and in front of the pole of the same name, repulsion ensues: the suspended magnet turns until a position of equilibrium is attained. The repulsive force of the two magnets is measured by the sum of the two forces, the terrestrial magnetic force on the one hand, and the force of torsion developed in the thread on the other. If now, by the rotation of a micrometer situated at the upper part of the instrument, the two poles are gradually brought nearer together, and if, at each operation, the intensity of the repulsive force is measured, the law which Coulomb discovered will be proved: it is as follows:—

Magnetic repulsions vary in the inverse ratio of the squares of the distances through which they are exercised.

By another method, which consists in counting the number of oscillations which a magnetic needle makes when one of its poles is placed in the presence of the pole of contrary name of another magnet, at different distances, Coulomb proved that the same law of variation in inverse ratio of the squares of the distances, applies to magnetic attractions as well as to repulsions. We shall hereafter find that it also governs electrical forces.

At the commencement of this chapter we said that masses of steel are capable of acquiring the properties of natural magnets: to obtain this result several processes are used, which we shall now describe.

The oldest mode of magnetization is that of single touch, which consists in placing the pole of a magnet in contact with one of the extremities of a tempered steel bar. After a certain time the bar is found to be magnetized, with a pole at each of its extremities. A more powerful magnetization is obtained by passing the magnet several times from one end to the other of the bar which is to be magnetized (Fig. 343). The touching ought always to be done with the same pole and in the same direction. The pole *a*, obtained at the extremity at which the movement begins, is of the same name as the pole A of the magnet which is placed in contact with the steel bar.

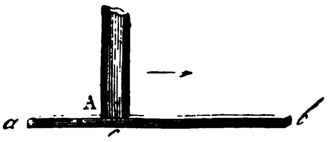

FIG 343. – Processes of magnetization. Method of single touch.

There are several methods of magnetization—discovered about the middle of the last century—which are distinguished from the first by the term of double touch, because two magnets are used instead of one. We shall only describe the methods of Æpinus and of Duhamel.

The bar to be magnetized, *a b*, is placed with its two extremities on the contrary poles of two powerful magnets, A′ B′, two other magnets, A, B, are then taken, which are inclined from 25 to 30 degrees over the middle of the bar, the two contrary poles are placed opposite to each other, and care is taken that each of these poles is on the side of the pole of the same name belonging to the fixed magnets A′ B′. If the moveable magnets are passed in the opposite direction several times without changing their inclination, the polar magnetism is developed in the steel bar, which acquires two poles, *a b*, of contrary names to the poles B B′, A A′ of the magnets used. This is Duhamel's process; it gives powerful magnetization, but not at all regular, and it sometimes produces consequent points. The process of Æpinus only differs from that of Duhamel by the two moveable magnets being inclined from 45 to 50 degrees, and after having placed them in contact and bound them together at the middle of the steel bar, both are passed together from one extremity of the bar to the other. The magnetization thus obtained is not only more powerful than the preceding, but more regular. Therefore the separate double touch is preferred when needles are to be magnetized for compasses.

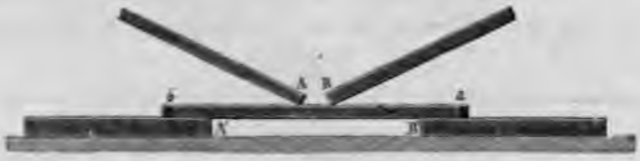

FIG. 344.—Magnetism by separate double touch. Duhamel's process.

Steel, or even soft iron bars, can be magnetized without the use of artificial or natural magnets, if they are placed in the plane of the magnetic meridian and in the direction of the inclination. In this position a steel bar is magnetized along its whole length, and obtains all the properties of a magnet: a bar of soft iron becomes a magnet, but only a temporary one; the magnetic action of the terrestrial globe magnetizes by influence, or induction as it is called.

If one of the extremities of a magnet thus produced is struck with a hammer, the magnetic force of the bar is not only increased but it becomes permanent.

Pieces of wire strongly stretched whilst held in the direction of the dipping needle are magnetized; and if they are united by their poles of similar name in a single sheaf, a very powerful magnet may be obtained. To magnetize by the action of terrestrial magnetism, it is sufficient to hold the bar of iron or steel vertical while one of its extremities is struck with a hammer. In this manner this bar is in the plane of the magnetic meridian, but without the inclination of the magnetized needle.

This action of the earth well explains how it happens that in shops in which steel and iron are worked, a great number of tools become magnetic, shovels, pincers, iron-work of windows, and generally all the pieces of iron-work which are a long time in a position perpendicular to the horizon; this is also the case with the crosses which surmount church towers. We shall soon have occasion to speak of the magnetism obtained by electric currents, but it was known for a length of time that lightning could communicate magnetic properties to iron. In the article *Magnet* in D'Alembert and Diderot's Encyclopædia we read: "One day lightning entered a room in which there was a box of steel knives and forks destined for sea use; the lightning entered by the southern angle of the room, exactly where the box was placed; several knives and forks were melted and broken; others which remained whole were strongly magnetized, and became competent to lift large nails and iron rings, and this magnetic virtue was so strongly impressed that it was not dissipated when they became rusty."

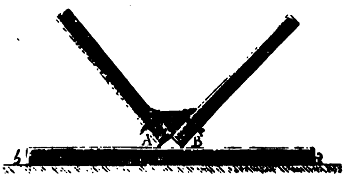

FIG. 345.—Magnetization by the method of Æpinus.

The strength of magnets alters in the course of time: shocks, changes of temperature, and lastly the action of the earth are the causes of this alteration. The strength depends on the volume of the magnet, its form, and the temper of the steel; thus, in two similar magnetized bars, the magnetic intensity is proportional t their size, or, in other words, to cubes of equal dimensions nevertheless, it has been noticed that small magnets are, in proportion, more powerful than large ones: some have been made which supported pieces of iron whose weight was a hundred times their own. This suggested the idea of forming magnets by uniting a series of magnetic bars by their similar ploes: these are called *compound magnets*. Fig. 346 shows how these magnets are arranged. In the Royal Institution of London there is a compound magnet formed of 450 plates, each of which is 40 centimetres in length. It is sufficiently powerful to lift 50 kilogrammes.

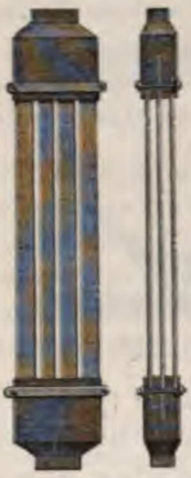

FIG. 346.—Compound magnet, formed of twelve magnetic bars.

Form also influences the strength of magnets; thus, with equal weights, a lozenge-shaped magnetic needle is more powerful than a rectangular bar.

The temper of the steel has a great influence on the force of the magnetized bar: tempered steel is magnetized more strongly than non-tempered steel; if it is subjected to increasing temperatures, the magnetic force is weakened more and more. Coulomb has shown, however, that the result is quite different, if, instead of working with rectangular bars, very fine and long needles are employed; in this case heating increases their magnetic force.

Lastly, temperature has a great influence on the force of magnets. A magnetic bar when heated to redness loses all its magnetism, the intensity diminishing as the temperature rises, as stated by Coulomb. But if the variations of heat take place within narrow limits, the magnetic intensity varies only slightly, and the magnet resumes in cooling the strength which it originally possessed. This refers to polar magnetism, that is to say, to that possessed by magnets; but it is also the case with simple magnetic substances like soft iron, nickel, &c., which also lose their property when their temperature is raised to a certain degree. Iron is not magnetic if it is heated to a cherry red-heat, and the same happens in the case of cast-iron heated to whiteness. Above 350°, nickel is no longer magnetic, and manganese only becomes so below zero, about $-20°$. These last results are due to M. Pouillet.

We have now to speak of the means employed to preserve the magnetic force in natural and artificial magnets. Experiment has proved that magnetic bars, united parallel to each other, two by two, in a box, so that the opposite poles are together, preserve their magnetism, if care is taken to join the contrary poles by bars of soft iron, which are called *armatures* or *keepers*.

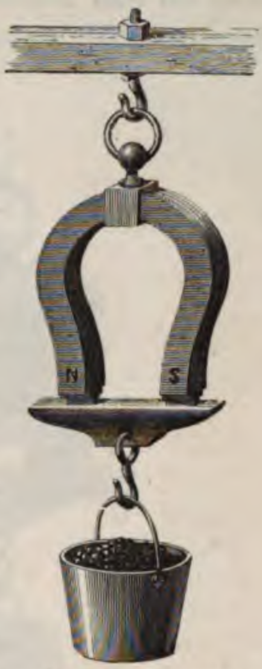

FIG. 347.—Iron horse-shoe magnet, with its armature and keeper.

An armature is used to increase the power of a magnet. When these are used it is sometimes curved in the form of a horse-shoe, the armature uniting the two poles.

A magnet armed in this way (Fig. 347) carries not only a greater weight than that which a single pole would carry, but double that weight. By uniting two rectangular magnets or compound magnets, turned so that their opposite poles A, B are joined by a similar armature (Fig. 348), a very strong magnet is obtained. Experiments also show that magnets thus arranged keep their magnetic force better if they are left armed with their keepers, or if the charge of iron that they are able to lift is suspended on it, always provided that it does not exceed that limit; for then, the keeper being suddenly detached, the magnetic force of the magnet is weakened.

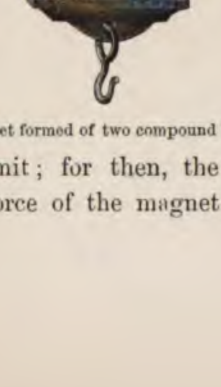

FIG. 348.—Magnet formed of two compound bar magnets.

Masses of magnetic oxide of iron, which constitutes natural magnets, have often but feeble magnetism; but their magnetic virtue has been increased by furnishing them with pieces of soft iron conveniently arranged. Fig. 349 shows how these armatures are placed: *m m′* are plates of soft iron with which the natural magnet is enclosed, and which are terminated by thicker masses *p p′*, these forming real poles to the magnet; C is the armature or keeper. Finally plates of copper are used to support the plates of soft iron round the mass of magnetic oxide.

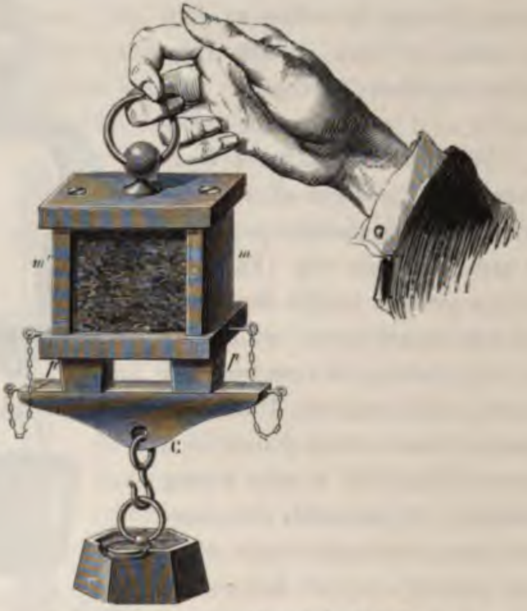

FIG. 349.—Natural magnet furnished with its armature.

BOOK VI.

ELECTRICITY.

BOOK VI.

ELECTRICITY.

CHAPTER I.

ELECTRICAL ATTRACTION AND REPULSION.

Attraction of amber for light bodies—Gilbert's discoveries; electricity developed by the friction of a number of bodies—Study of electrical attraction and repulsion; insulators, or bad conductors; good conductors—Electrical pendulum—Resinous and vitreous, positive and negative electricity—Laws of electrical attraction and repulsion—Distribution of electricity on the surface of bodies—Influence of points.

THE ancients discovered that amber, when it is quickly rubbed with a piece of woollen stuff, and brought near light bodies such as bits of straw, pieces of paper, or feathers, causes them to move towards it, as if attracted by some mysterious force. Thales of Miletus, who lived 600 years before the present era, mentioned this property; and the Greek philosopher, Theophrastus, speaks of jet as likewise possessing it. But to these two facts alone, during more than two thousand years, the knowledge of physicists was confined, so far as this class of phenomena is concerned. Pliny the naturalist, on mentioning the first fact, stated that "friction gives to amber heat and life."

About the year 1600, an English doctor, William Gilbert, to whom science owes many discoveries concerning the properties of the magnet, discovered that glass, sulphur, resins, and various precious stones possessed the attractive properties of amber. Since that time a great number of physicists have extended the researches of Gilbert, and

Indeed, after rubbing a glass tube closed with a cork stopper, we perceive that the stopper itself is electrified, although the cork rubbed separately does not give any sign of electricity. Gray studied this transmission of electricity, and proved that it could take place through a great distance, through bodies which until then were considered incapable of being electrified by friction. On the other hand, this transmission cannot take place with substances capable of being directly electrified under the conditions previously stated. It follows from these experiments, that different substances possess in different degrees the property of conducting electricity once developed: bodies which were before considered as only susceptible of being electrified by friction, are precisely those which conduct electricity the least—they are *bad conductors*. Those, on the contrary, which it had been found impossible to electrify, are *good conductors*. The consequences of this new distinction are important, and we shall see they are proved by experiment. As glass, amber, resin, &c. are bad conducting bodies, electricity can only be developed in the rubbed portions; and this is proved by observation. But if they are touched by the hand, which is a good conductor like the rest of the body, electricity passes to the latter, then to the ground, and disappears always at the points where contact takes place. We have seen that it

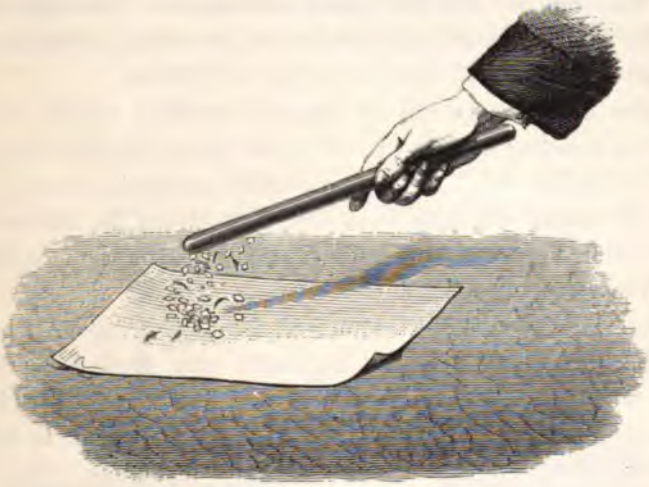

FIG. 350.—Attraction of light bodies.

quite disappears if the hand is passed over the whole surface of the electrified rod. When a metallic cylinder is rubbed, it will be understood that no sign of electricity can manifest itself; and, indeed, as metals are excellent conductors, if electricity is produced, it instantly extends over the whole surface of the metal, and, through the intervention of the body of the operator, passes to the ground. If a handle made of some bad conducting body, glass for instance, is fitted to the metallic cylinder, and if this handle is held in the hand whilst the metal is being rubbed, the latter becomes electrified and acquires the properties which we have described above as belonging to glass resin, and amber. For this reason the name of *insulating bodies* is given to bad conductors ; by insulating any substance whatsoever, it becomes susceptible of being electrified by friction.

These experiments can be repeated under a variety of forms. A person standing on a stool with glass legs is electrified when he is rubbed with the skin of a cat ; on placing the finger near any part of his body sparks will pass from him, and during the whole time of electrization he perceives a singular sensation on the face, like that caused by an electrified rod.

Water is a good conductor ; and in the state of vapour it possesses the same property. This is the reason why great care must be taken when electricity is being obtained, not only to insulate the substance operated upon if it is a good conductor, but to wipe and dry the handle or glass supports, or other insulators. This is also the reason why electricity is produced with greater facility in dry than in damp weather ; the room in which the experiments are made must be dried as much as possible previously, so that the air which it contains may contain as little aqueous vapour as possible. To avoid the escape of electricity by the insulating glass supports which are generally employed in electrical apparatus, they are covered with a layer of shellac varnish, the surface of which is not hygrometric like that of glass.

Various substances may be arranged according to their order of conductibility in two classes, viz. into good and into bad conductors or insulators, but in each of them the conducting property is affected in different degrees, so that no substance is absolutely without it. The following table gives a few substances arranged in the order of their decreasing conductibility :—

Good conducting bodies.	Bad conducting or insulating bodies.
Metals.	Ice.
Burnt charcoal.	Phosphorus.
Graphite.	Caoutchouc.
Acidulated water.	Porcelain.
Minerals.	Dry air.
Water.	Silk.
Vegetable substances.	Glass.
Animal substances.	Sulphur.
Steam.	Resin.
Powdered glass.	Amber.
Flour of sulphur.	Shellac.

From this it is seen that electrical conductibility is not influenced by the chemical nature of the substance, so much as by its physical condition or molecular structure. Thus ice is in the number of the insulators, whilst water and steam are amongst the conductors. Sulphur and glass in large masses are bad conductors; but when reduced to very fine powder they conduct electricity very readily. Coal in the ordinary state is an insulator, but it becomes a conductor when calcined; carbon crystallized, or in the state of diamond, is a bad conductor, but graphite, which is another mineralogical form of

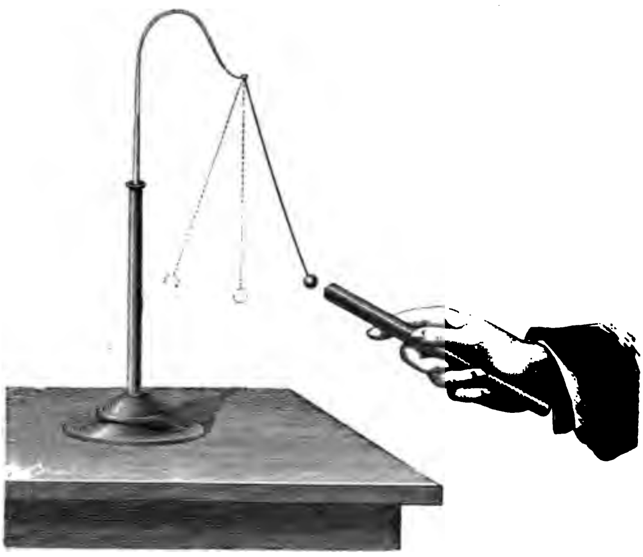

FIG. 351.—Electrical pendulum. Phenomena of attraction and repulsion.

carbon, is a good conductor. Heat has great influence on the electrical conductibility of bodies; a high temperature confers this property upon several bodies which are insulators at the ordinary temperature; glass, sulphur, shellac, and gases, are among this number.

We will now return to the phenomena of electrical attraction and repulsion, and study them in greater detail.

We shall for this employ a very simple instrument, to which the name of the *electrical pendulum* (Fig. 351) has been given. It is a little ball of elder pith suspended by a silk thread to a stand, and is consequently insulated, as silk is a bad conductor. By holding near the pith ball a rod of electrified resin, we observe that there is first attraction; but, so soon as contact has taken place, the ball is repelled from the resin, and this will continue to be the case even when the rod of resin is again brought near to it. In this state, the pith ball is electrified, which is easily seen by holding the finger to it, for then it is attracted; on touching it with the hand, after contact with the resin, it is neither attracted by the finger nor repelled by the rod of resin; the electricity which it possessed has passed into the earth, through the body of the operator. If, instead of using a rod of resin, an electrified glass rod is employed, the same phenomena manifest themselves in the order we have just described: there is attraction and contact, then repulsion. So far, no difference has been observed between the electricity developed on the resin and that developed on the glass, when these two bodies are rubbed with a piece of cat-skin or silk. But let us suppose that after having obtained the repulsion of the pith ball by means of the electrified resin, a glass rod electrified by cat-skin is brought near the pith ball. The pith ball is now attracted by the glass as strongly as if, instead of having been previously electrified by resin, it had remained in its natural condition. The same phenomena of attraction will be manifested, if, after having electrified the ball by contact with the glass rod, a piece of resin electrified by cat-skin or silk is placed near it.

Thus the electricity developed on the resin and that developed on the glass by friction of the cat's skin or silk acts under the same circumstances, in an opposite manner; for the one attracts the electrified body which the other repels, and reciprocally. Hence, electricity was distinguished by the earlier experimenters into two kinds, and the names given were *resinous electricity* and *vitreous* *electricity.* On repeating the preceding experiments with amber, sulphur, wax, paper, &c., it will be seen that these substances act, some like the resin and others like the glass; and it is then said that they are charged either with resinous electricity, or with vitreous electricity. These terms are now abandoned, and for the following reason:—As all bodies are capable, as we have just seen, of being electrified by friction, it is clear that if one of the rubbed bodies is electrified, the other must be electrified as well; and this is confirmed by experiment. But it has been shown, besides, that electricity developed on one of the bodies is not the same as that developed on the other; for example, if two discs are taken, one of polished glass and the other of metal covered with cloth, each furnished with an insulating handle, and if after they have been rubbed against each other they are suddenly separated, the glass disc will be found charged with vitreous electricity, and the cloth with resinous electricity, as may easily be proved on trying the action which each of them exercises on an electrical pendulum, the ball of which has been previously electrified in the same manner in each case.

But this is not all; it will be noticed that the nature of the electricity developed on a body changes *according to the body with which it is rubbed:* thus, glass, which we have seen taking up vitreous electricity when it is rubbed with silk, on the other hand takes resinous electricity if it is rubbed with cat-skin. Shellac becomes charged with resinous electricity if it is rubbed with a cat's skin or flannel; while it acquires vitreous electricity if it is rubbed with a piece of unpolished glass. By retaining the terms we have just used, a certain confusion may occur, for which reason the names of *positive* and *negative* electricity have been substituted for those of vitreous and resinous electricity. Moreover, we must not attach to these words other signification than this: positive electricity is that developed on glass by rubbing it with silk; negative electricity is that obtained on resin by rubbing it with cat's skin. But the method of action of these two kinds of electricity may be summed up in two very simple laws: 1st, *All bodies electrified either positively or negatively attract light bodies in their natural state.* 2. *Two bodies charged with electricities of contrary names attract each other; two bodies charged with electricities of the same name repel each other.*

There is no exception to these laws, but the conditions of production of one or the other kind of electricity are extremely complex; the same substance, we have just seen, is sometimes electrified positively and sometimes negatively, according to the substance with which it is rubbed. But modifications, often but slightly apparent on the surface of bodies, change the nature of the electricity developed. Thus polished and unpolished glass, both rubbed with cat-skin, take, the first, positive electricity, the second, negative electricity: two discs of similar glass rubbed against each other are electrified sometimes in one way and sometimes in another; heat possesses great influence, and the greater number of hot substances acquire negative electricity.

Many curious experiments have been made as to the conditions which determine one or the other mode of electrization; but little is as yet known as to the causes of these singular phenomena, and the theories which have been started to explain them have no greater advantage than to classify the facts, and thus render them more easy to fix in the memory.

An insulating body, or a bad conductor, can be electrified either by friction or by the contact of another body already electrified. We shall soon see another mode of electrization, which consists in developing electricity, at a distance, by *influence* or *induction*. It is in all cases interesting to know how the electricity is distributed in a body; if it spreads itself through the entire mass or only on the surface—if, in every part where its presence is manifested, it exerts the same energy—in a word, what is its tension in the different parts of bodies of different form.

One of the facts which experiment has already revealed to us is, that in an insulated body, electricity is located on the surface which has been rubbed, or which has been placed in contact with an electrified body. This is the case with the most perfect insulators; in bodies possessing a less degree of insulation, electricity extends to a little distance round the parts of which we speak. The reason of this fact is evidently the same as that which makes these bodies bad conductors of electricity. On the other hand, in good conductors, electricity, in whatever mode it may be produced, spreads itself almost instantaneously over the whole surface. Experiments which we are about to describe prove that it does not penetrate into the mass of the body, or, at least, that the thickness of the electrified stratum is very small.

A metallic sphere insulated on a glass foot is covered with two thin hemispherical envelopes, which are held in contact with it by two insulating handles; the whole system is then electrified, and both hemispheres are suddenly withdrawn. On separately presenting to the ball of an electrical pendulum, first the sphere itself, then each of the coverings, we shall observe that these latter are alone electrified. The electricity was not therefore spread out to a greater thickness than that of the envelopes. A hollow metallic sphere, pierced with a hole at the top and placed on an insulating stand (Fig. 353), is charged with electricity; and in order to ascertain the manner in which the electricity is distributed, a small gilt paper disc is used, furnished with an insulating handle—this is called a *Carrier* or *proof plane*—and it is applied to any point of the outer surface of the electrified sphere: it is then found that it attracts the pith ball of the electrical pendulum. The proof plane is now touched with the hand; the electricity with which it was charged passes away, and it returns to its normal condition: if it is now applied to the interior of the sphere, care being taken that it does not touch the sides of the hole, no sign of electricity will be shown on withdrawing it and presenting it to the pith

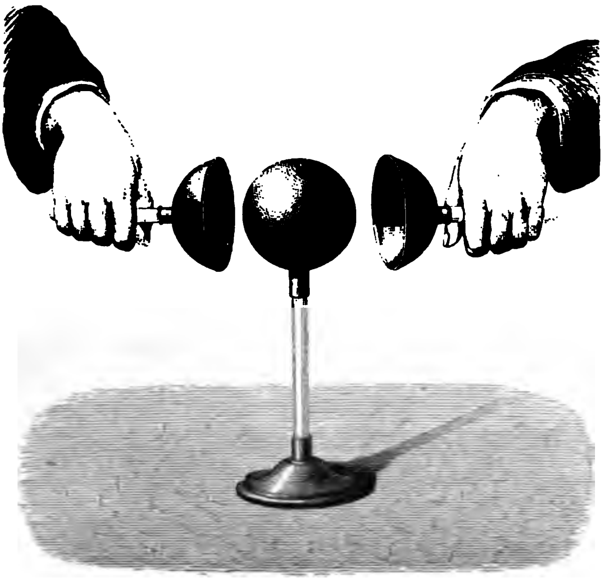
FIG. 352.—Distribution of electricity on the surface of conducting bodies.

ball. The result will be the same if the interior of the sphere is first touched. Faraday made the same experiment by giving to the body the form of a cylinder of metallic network, which he placed on an insulated disc of brass; the disc was then electrified, and he proved, by the help of the proof plane, that the electricity was located alone on the outer surface of the vessel.

The same illustrious physicist also made the experiment with a conical bag of muslin, attached to an insulated metal ring: the latter is electrified; and a double silk thread, fixed to the top of the cone, enables the bag to be pulled inside out, and it is always found that the electricity is on the outer surface, so that it passes alternately from one surface of the bag to the other (Fig. 354).

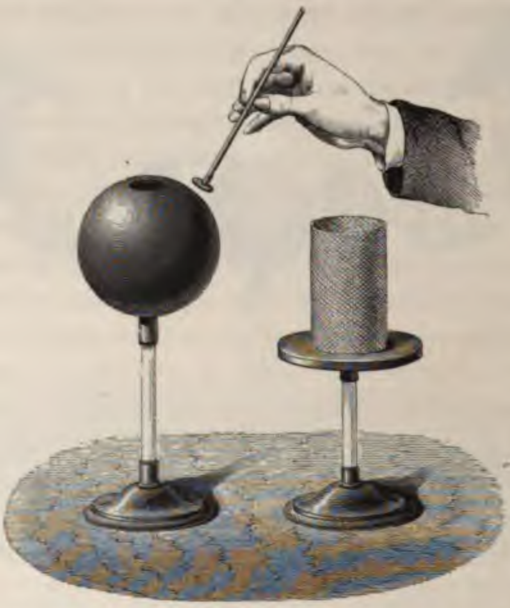

FIG. 353.—Distribution of electricity on the surface of bodies.

Thus it is entirely on the outer surface of conductors that electricity is distributed: at least, if it penetrates into the interior, the thickness of the electrified stratum is extremely small. Let us take two spheres, one plain and of metal, the other of shellac, gilt on the outside, both being of the same diameter; and then electrify the first, and measure the electric tension by means of an instrument called an electrometer. If the spheres are now placed in contact, the electric tension on each of them is found to be half what it was at first on the single metallic sphere. As the thickness of the electric stratum on the shellac sphere is equal to that of the gold leaf, we must conclude that its thickness is not greater on the solid sphere.

We have just spoken of electric tension. It is the intensity of the force with which a given portion of the surface of an electrified body attracts or repels an electrified body exterior to it. Coulomb, under the name of the *electric balance*, devised an instrument which is used to measure this tension, and by means of it he determined the laws according to which electric attractions and repulsions take place under varied conditions. As the principle of this instrument and the mode of observation is the same as in the case of the magnetic balance, described in the preceding Book, we shall content ourselves with simply stating the following laws.

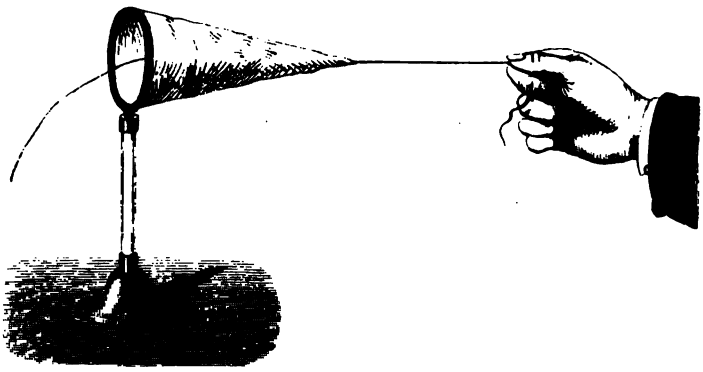

FIG. 854.—Faraday's experiment to prove that electricity is located on the outer surface of electrified bodies.

The repulsion or attraction of two equal spheres charged with electricities of the same or contrary kinds, varies in the inverse ratio of the square of their distances. Attractive or repulsive forces vary as the products of the quantities of electricity which the two spheres contain.

This, it will be remembered, is the law which governs universal gravitation.

The tension of electricity spread over the surface of a conducting body is only equal at each point of the surface, when the body has the form of a sphere. This is expressed by saying that the thickness of the electric stratum is uniform (Fig. 355).

In an elongated ellipsoid, this stratum possesses its maximum thickness at the extremities of the major axis; in a flattened ellipsoid, the maximum is round the equator. In a flat disc, the electric tension, which is nearly *nil* at the centre, increases towards the edges, where it attains its greatest intensity. In a conductor formed like a cylinder terminated by two hemispheres, the tension is greatest at the surface of these latter; and it is nearly *nil* everywhere else. The dotted lines surrounding the solids represented in Figs. 355 and 356, indicate, by their distances from the adjacent points of the surfaces, the tension of the electricity at each of these points.

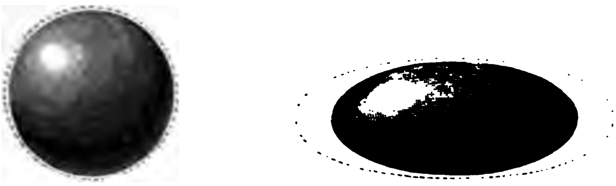

Fig. 355.—Tension of electricity at the different points of a sphere and of an ellipsoid.

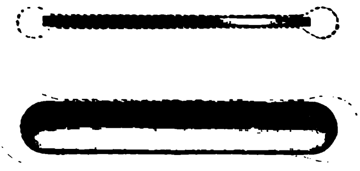

Fig. 356.—Tension of electricity on a flat disc, and on a cylinder terminated by hemispheres.

We see, therefore, what a great influence form has on the distribution of electricity on surfaces; but nowhere is this influence so perceptible as on the parts of bodies terminated by abrupt edges, acute angles, and conical or pyramidal points. At these parts electricity accumulates, and acquires sufficient intensity to pass into the surrounding medium, even when this medium is only to a slight extent a conductor. Before experimentally proving what is called the *power of points*, we may say a word or two on the influence of the medium which surrounds an electrified body, on the preservation or loss of the electricity on its surface.

We already know that if this medium is a good conductor, such as water or moist air, the electricity will not remain on the body which has been electrified, but will pass away: this is an obstacle which must be removed, however slight it may be, if we wish to acquire a quantity of electricity. But if the medium is dry air, let us inquire what will be the influence of atmospheric pressure on the loss of electricity from the surface of a body, and what the influence of temperature? These questions are very complex, because the causes which act at one time on the loss of which we speak, besides being numerous, are very difficult to study separately. The insulating supports are more or less conductors; and the same remark applies to electrified bodies. Coulomb and Matteucci studied this interesting and difficult question, and did not always arrive at similar results. Nevertheless, their researches have shown that the loss of electricity in dry air increases with the temperature; that with a constant temperature it increases rapidly when the pressure of air diminishes, or rather as the air surrounding the electrified body is rarefied. Nevertheless, this last law only holds good in the case of strong charges; so that, if we introduce an electrified body into a vacuum, it immediately loses the greater part of its tension; but this action is limited, after which the loss goes on very slowly. The greater the rarefaction, the less is the limit, but the loss of electricity becomes less also. We shall hereafter describe some very curious phenomena, which show the loss of electricity in rarefied media.

We will now return to the escape of electricity at points.

It has been calculated that at the top of a conical point the electric tension is infinite, so that it is impossible to charge a conducting body, furnished with such a point, with electricity; this is confirmed by experiment. In proportion as the electricity is developed, it escapes into the surrounding medium and disappears. When the extremity of the point is examined in the dark, a luminous tuft is seen, the form and colour of which we shall hereafter study. If, while the point is in communication with the electric source, the hand is placed before or under it, a wind is felt which indicates a continuous movement of the particles of air; this movement is rendered very perceptible by placing at the end of the point the flame of a candle (Fig. 357). The *electric wind* is intense enough to cause the flame to bend, or even to extinguish it. This agitation of the air, at the extremity of the points of electrified conductors, was at first attributed to the escape of the electricity, which was compared to a fluid; but the following explanation appears to us preferable, because it requires no hypothesis as to the nature of electricity, and is, moreover, found to agree with known phenomena.

The molecules of air, which are in contact with the point electrified to a considerable degree of tension, are charged with electricity of the same name as that of the conductor; then commences repulsion, and the molecules, on getting further away, give place to others, which are electrified in their turn, and so on. Hence the current of air which observation indicates, and which is only continuous so long as the electric charge is renewed.

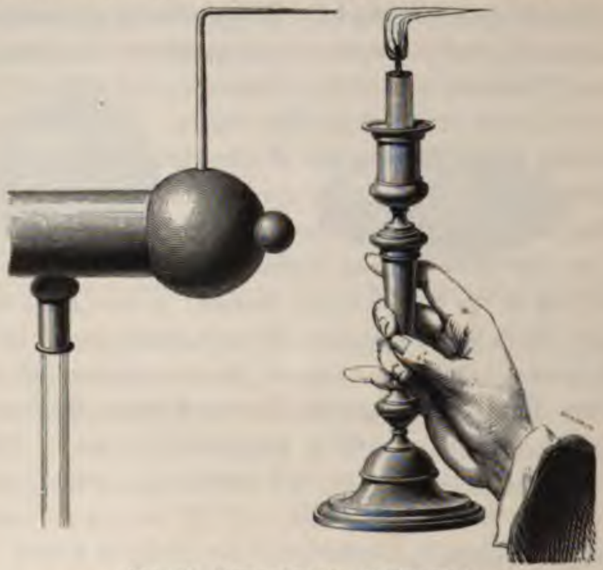

FIG. 357.—Power of points. Electric wind.

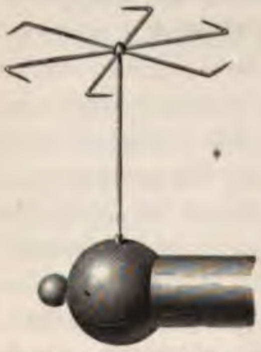

FIG. 358.—Electric fly.

The force with which the air is driven from a point, engenders a reaction, which must repel the point in a contrary direction; and if this point does not move, it is because it is not free to do so. The existence of this reaction is proved by using a little instrument called the *electric fly* (Fig. 358). A system of divergent wires is united by a centre piece, which allows the movement of the system in a horizontal plane; each wire is curved in and sharply pointed in the same direction. As soon as the conductor on which the fly is placed is charged, the latter takes up a rotary movement in the direction opposite to that of the points.

CHAPTER II.

ELECTRICAL MACHINES.

Electrification at a distance; development of electricity by induction—Distribution of electricity on a body electrified by induction—Hypothesis as to the normal condition of bodies; neutral electricity proceeding from the combination of positive and negative electricities—Electroscopes; electric pendulum; dial and gold-leaf electroscopes—Electrical machines: Otto von Guericke's machine; Ramsden, or plate-glass machines; machines of Nairne and Armstrong—The electrophorus.

WHEN a body is in its normal condition, we have just seen that there are two modes of rendering it electrical, viz. by friction, or by contact with a body previously electrified. The phenomena which we are about to describe prove that, in the latter case, contact is not necessary. Let us take, for instance, an electrified body C—a metallic sphere mounted on a glass column—and let us place in its vicinity, a short distance from it, an insulated cylindrical conductor A B, in its natural condition. These two bodies are no sooner in the presence of each other, than the conductor A B shows

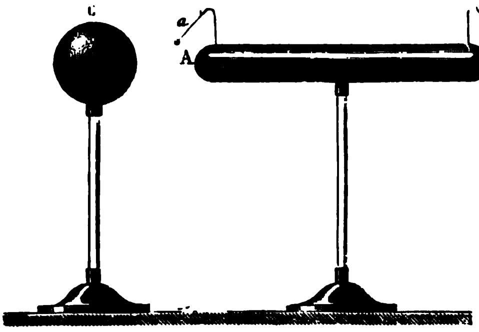

FIG. 359.—Electricity developed by influence or induction.

signs of electricity, as may be proved by bringing the pith ball of an electric pendulum near its extremities, when it is immediately attracted by the conductor; or still better by observing the small pendulums *a*, *b*, fixed at different points of the cylinder, and formed of pith balls suspended by conducting threads. These balls are charged by contact with the same electricity as the parts which they touch; hence, the repulsion which is shown by the deviation from the vertical of the pendulum threads. This method of evoking electricity, developed at a distance by an electrified body on a conductor in its natural state, is called *electrization by influence* or *induction*. Let us determine the nature of this electricity, and the manner of its distribution on the conductor. If the sphere C is charged with positive electricity, the extremity A of the cylinder, nearest the sphere, is electrified negatively; the extremity B is, on the contrary, electrified positively. This can be seen, by presenting successively to the two extremities a small insulated pendulum, the ball of which is charged with a certain electricity; for instance, positive electricity. When held near A, it is attracted; but when near B, it is repelled. The reverse would take place if the sphere C had been charged with negative electricity.

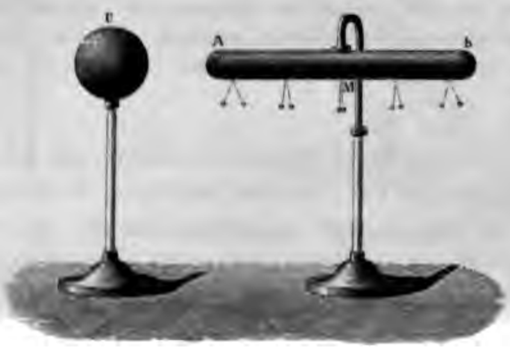

FIG. 360.—Distribution of electricity on an insulated conductor electrified by induction.

To study the distribution of these two opposite electricities on the conducting cylinder, double pendulums with conducting wires or threads are suspended at different distances, so that the divergence of the balls can be observed. It will then be seen that the electrical tension is at a maximum at each extremity, and that it gradually diminishes from each of these extreme points towards a mean position M, where it disappears, and for this reason it is called the *neutral line.* But this section of the cylinder which has thus remained in its natural state, is closer to the extremity nearest to the sphere than to the other; it is not absolutely at the centre of the conductor electrified by induction. We may also add that the electric tension is greater at A than at B. Matters being thus arranged, let us gradually remove the sphere. The balls of the pendulum will then be seen to gradually approach each other, and to return to contact when the distance of the sphere is sufficiently great. Then all the influence ceases; the conducting cylinder returns to its natural state; it also immediately regains this state if, instead of removing the sphere, the latter is discharged of its electricity by placing it in communication with the ground.

In the experiment just described, the conductor electrified by induction was insulated. Let us suppose that after having placed it in the presence of the inducing sphere—the charged body which electrifies by influence is thus called—the furthest extremity B is made to communicate with the ground: immediately all the electricity with which this part of the cylinder was charged disappears, and this latter only contains the electricity opposite to that of the sphere, but at a greater tension, as the more considerable divergence of the pendulums proves: the maximum of tension is always at A, and the neutral line has disappeared. The nature of the remaining electricity, its distribution on the conductor, and its tension at the different points would still be the same, if, instead of touching it at B, every other part of the cylinder is made to communicate with the ground, even the extremity A. Indeed, if after having established this communication it is removed, all remains in the same condition; that is to say, the conductor is always charged with electricity opposed to that of the inducing sphere, unequally distributed. On removing this sphere, the electricity remains on the conductor; but it is distributed equally over every part of its surface, and we now have a body electrified by induction and charged with electricity, as if it had been directly charged by friction, or contact.

When we place in the presence of a source of electricity, such as the sphere, not only one conductor, but a series placed in a row A B, A′B′, &c. (Fig. 361), they are all simultaneously electrified by induction; but the electric tension on each of the cylinders gradually diminishes with the distance, although it is stronger on A′ B′, for example, than it would be if the conductor A B were taken away, and the induction was only exercised by the sphere alone. This last observation proves that each conductor acts by induction, and contributes to electrify that which follows it in the series.

The preceding facts are of great importance, and they have suggested an hypothesis which, without theorizing as to the nature of the first cause of electricity, gives a complete explanation of the phenomena of attraction and repulsion, and electricity by contact, &c. This hypothesis may be stated as follows:—A body in its natural condition possesses simultaneously two kinds of electricity—positive and negative—in such proportion that they neutralize each other. If it is rubbed with a second body, a separation of the two electricities is produced: one kind passes to one of the rubbed bodies, and the other to the other, where they each find themselves in excess when the bodies are removed, and they then manifest their presence by the phenomena which we have described.

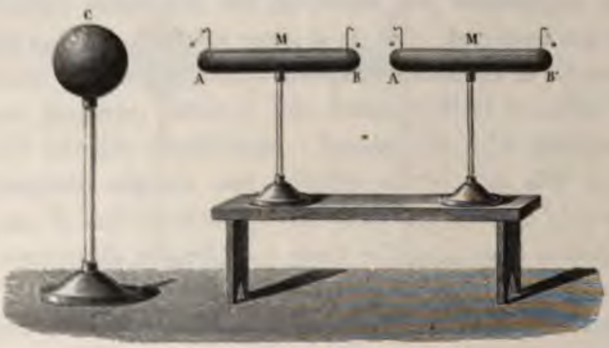

FIG. 361.—Electrical induction through a series of conductors.

It is by this means that electrization by induction is explained; that is to say, the phenomena presented by the conducting cylinder placed in the vicinity of the electrified sphere. The positive electricity of this sphere attracts the negative electricity and repels the positive electricity of the conductor; the first is attracted towards the extremity A (Fig. 359), the second is repelled towards the extremity B. But the attraction is stronger at A than the repulsion at B, because the distance from the source is less at the first region than at the second: this is the reason why the neutral line D is nearer to A than B. When the conductor is placed in communication with the ground, it is the same as if it had been indefinitely lengthened, which explains the increase of tension of the negative electricity at A; the neutral line indefinitely removed further back is no longer on the cylinder, so that if the communication is suddenly broken, negative electricity alone will be found on it. This latter is also found to be unequally distributed on the surface, on account of the inequality of action of the sphere on portions which are situated at increasing distances. The same hypothesis will account for the first phenomena that we studied; that is to say, attraction and repulsion of light bodies by an electrified body.

If the pith ball of an electrified pendulum is brought near a glass rod C, charged with positive electricity, the neutral electricity of the ball is decomposed by induction; the positive is repelled to *b*, if the thread is an insulating one, or sent back to the ground if it is a conducting one; the negative is attracted to *a*. In both instances, the tendency of the positive electricity of the ball and the negative electricity of the rod to reunite, causes the pendulum to deviate from the vertical: and attraction ensues. If there is contact, the electricities combine, and the ball remains charged with negative electricity, always provided that it is insulated; hence, repulsion between the two electricities of the same nature, which the two bodies contain at this moment in the presence of each other. When the ball is not insulated, the positive electricity passes to the ground, and contact determines the combination of the two contrary electricities; the ball then returns to its natural condition, and there is no repulsion. These facts, as we have seen in the preceding chapter, are proved by observation.

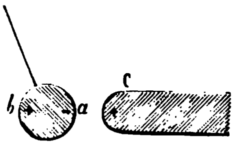

FIG. 302.—Cause of attraction of light bodies.

The electrization of an insulated conducting body by contact of a body already electrified is also easily explained: before contact the neutral electricity of the conductor is decomposed by induction; there is attraction of the positive electricity—let us say, of the body previously electrified—for the negative electricity of the conductor, and repulsion of the positive electricity. Contact determines the combination, in a certain proportion, of the electricities which attract each other, and there remains on the conductor an excess of positive electricity; hence there is a charge of electricity of the same nature as that of the electrical source, which at first caused it to be believed that electrization was caused by a flow of electricity somewhat similar to that of a fluid: and the hypothesis appeared the more true as contact diminished the electric charge of the source. In reality there is no division of electricity between the two bodies; but rather an action of decomposition by induction, than a partial combination. This combination often takes place through the air a little before contact, and it is, as we have seen, accompanied by a slight explosion and a spark.

Lastly, the action of points also finds a more complete explanation on the preceding hypothesis than on that which we vaguely indicated above. When a conductor terminated by a point is presented to an electrified body, the neutral electricity of this conductor is decomposed by induction; and as the electricity opposed to that of the electrified body possesses at the extremity of the point an infinite tension, it effects a rapid combination with the two electricities of contrary names, and the electrified body is found to be discharged.

These rather dry preliminaries are indispensable to the comprehension of the phenomena which we have to describe; indeed, without them, it would be impossible to understand the function of electrical machines, as well as the numerous experiments which they enable us to make.

Before commencing a description of these we may say a few words on the apparatus termed electroscopes, because they are employed to prove the presence of free electricity developed on a body, and to measure its tension.

The *electric pendulum*, which we have already described, is an electroscope, and we have pointed out many of its uses.

The *dial electroscope* or quadrant electrometer is represented in Fig. 363. It is formed of a conducting support, surmounted by an ivory scale; at the centre of the scale is suspended the rod of a pendulum with a pith ball; the rod is very thin and is also of ivory. When this apparatus is placed on a body charged with electricity, the latter pervades all parts of the electroscope. The pith ball, at first in contact with the support, is repelled, and its deviation from the vertical is indicated by the divisions of the scale, the angle being greater as the electrical charge of the body is greater.

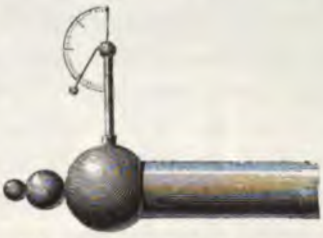
FIG. 363.—Quadrant electroscope.

The *gold-leaf electroscope* (Fig. 364) is composed of a glass bell-jar placed on a metal plate, to the interior of which passes a brass rod surmounted on the outside with a ball. This metallic rod supports two gold leaves which remain vertically in contact, when the electric charge of the apparatus is *nil*, and which diverge under contrary conditions. The following is the mode of using gold-leaf electroscopes when we desire to know whether a body is electrified or the reverse. The body in question is slowly brought near to the outer ball; if it is not charged with electricity, the leaves remain in contact: if on the contrary it is electrified, positively, for instance, the neutral electricity of the system formed by the ball, the metallic rod, and the gold leaves, will be decomposed by induction, the negative electricity attracted into the ball, and the positive electricity repelled into the gold leaves; these will then diverge, forming an angle between them varying with the electrical charge of the body. If we now touch the ball with the finger, the electricity of the same nature as that of the inducing body will escape to the ground; a fact which we have before proved in describing the phenomena of electrization by induction. The gold leaves will then approach each other, and the system will be charged with negative electricity, principally accumulated in the ball. If the finger and the inducing body are simultaneously taken away, this same negative electricity will be extended through the system and will cause the gold leaves to diverge again.

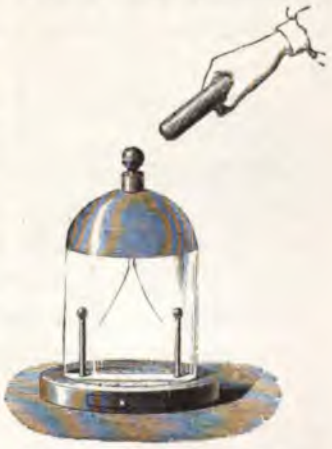
FIG. 364.—Gold-leaf electroscope.

The electroscope is, by this operation, charged with electricity which is always of a contrary nature to that of the body which has been presented to it. It is useful to learn how to distinguish the nature of this electricity when it is unknown. This is effected by the following means: a body charged with a known electricity is placed near the ball of the instrument, for instance a stick of resin electrified negatively; in the case we have supposed, that is to say, when the leaves are charged negatively, the influence of the negative electricity of the stick will manifest itself by an increased divergence of the gold leaves, the negative electricity of the rod being repelled into these, and the tension will thus be augmented.

If, instead of a stick of resin, a glass rod positively electrified is used, the contrary electricities of the gold leaf and the glass would be attracted; the divergence, instead of increasing, would be diminished until contact ensues. But in this case there might be a cause of error, because after the gold leaves have come in contact, the influence of the glass rod may determine a fresh decomposition, and hence a divergence. It is better, therefore, when there is not divergence at first, to make a second trial with a body charged with the contrary electricity.

Such are the proofs by the aid of which the nature of the electricity of a body can be determined when this body has been employed to charge the electroscope. It is evident that we might pursue a different course by charging the electroscope with a known electricity, and then using it to discover the kind of electricity which a body possesses.

ELECTRICAL MACHINES.

We already know that, by the aid of a body electrified by friction, it is possible to electrify another by induction. It is now time to describe the principal machines which have been invented for collecting positive or negative electricity; the construction of which is based, as we shall see, on these two modes of electrization.

The invention of the first electrical machine is due to Otto von Guericke; it consisted of a globe of sulphur or resin mounted on an axis, to which a rapid rotatory motion could be communicated. When the hands were pressed against this globe, the resulting friction rendered the non-conducting body electrical; and in order to collect the electricity thus developed, a metallic cylinder was suspended horizontally above the globe by silken cords. One of the extremities

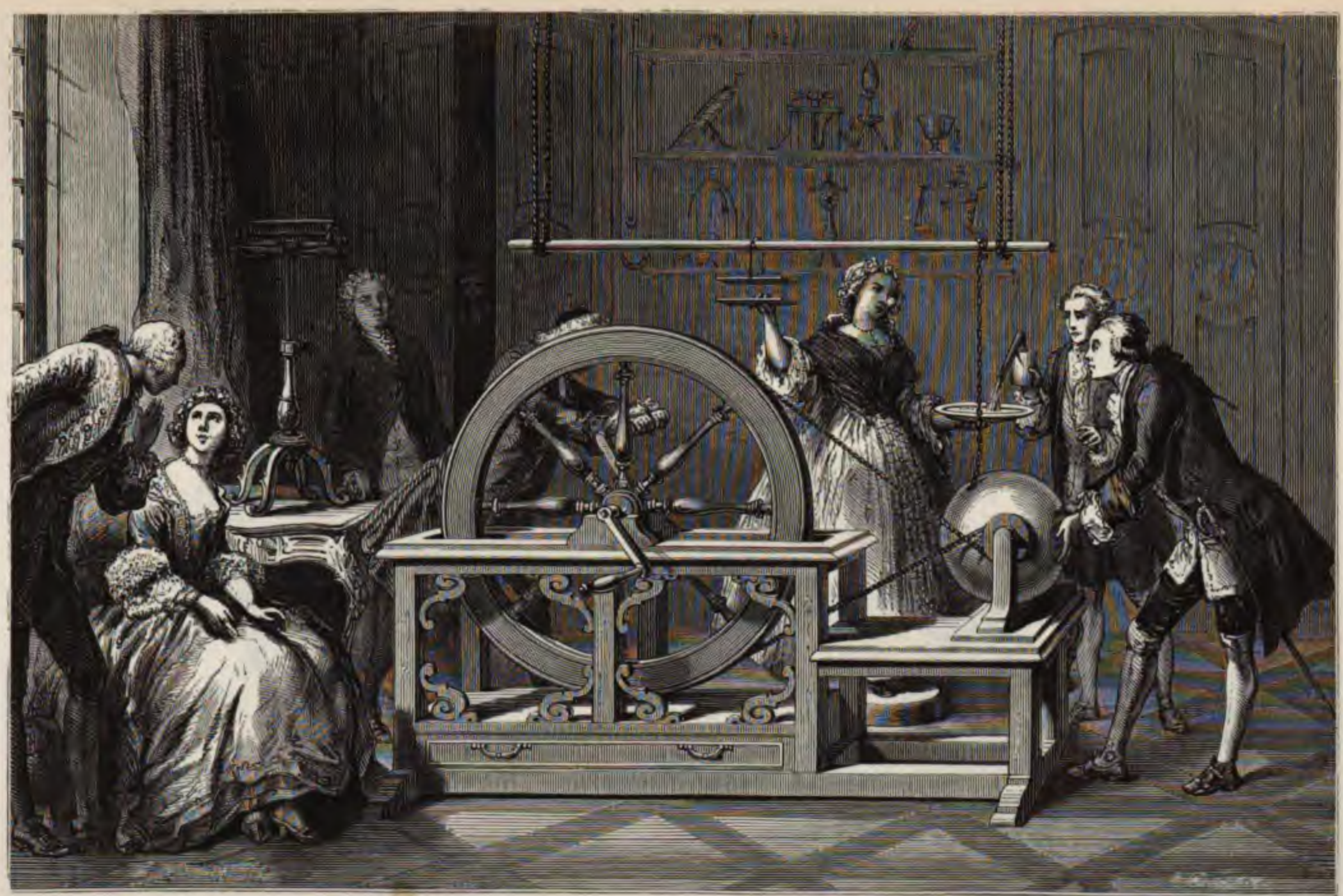

FIG. 365.—Otto von Guericke's electric machine.

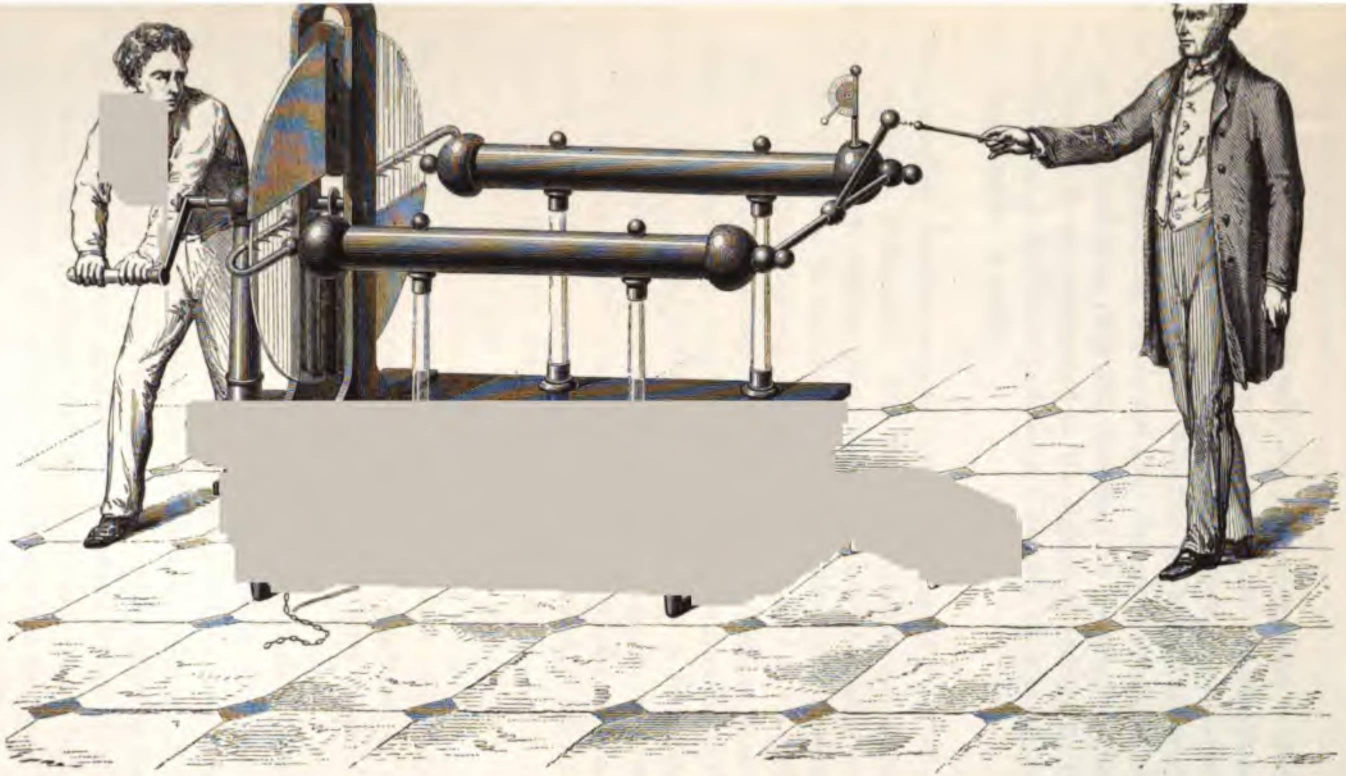

FIG. 366.—Plate electric machine.

of this cylinder was on a level with the globe of sulphur, or sometimes a metal chain descended from the conductor to a short distance from the surface of the globe. The electricity developed on the surface of the sulphur decomposed by induction the neutral electricity of the insulated conductor, which was thus charged at its extremities with opposed electricities. Fig. 365 represents an electrical machine of this kind as it was constructed in the eighteenth century, by the aid of which the Abbé Nollet performed a number of amusing and curious experiments in public.

The plate-glass electrical machine is the most generally used of all modern apparatus of this kind. Fig. 366 will render its construction intelligible. A large circular glass plate is mounted vertically on a metal axis, which can be turned by means of a handle; as it passes between the two wooden stands which support the axis of the plate, the surface of the glass rubs against two systems of cushions fixed to the stands. The rotatory movement thus produces electrization of the glass plate, which is charged with positive electricity on both sides. The cushions are not insulated, in order that the negative electricity with which they are charged may escape: if this electricity continued to accumulate on the cushions, a time would arrive when its influence on the positive electricity of the plate being equal to that due to the friction, would necessarily limit the charge; a metallic chain therefore puts the stands and cushions in communication with the ground.

The cushions are stuffed with horsehair, and covered with leather, the surface of which is covered over with aurum musivum, or an amalgam of zinc; experiment has proved that these latter substances facilitate the production of electricity.

Such is the arrangement of that part of the machine which produces the electricity; the conductors are charged in the manner now to be described. There are two long brass cylinders, with spherical ends, insulated on glass legs, the cylinders being united by a small transversal cylinder. The two extremities of these cylinders near the glass have metallic prongs, furnished with points, turned towards the glass plate, but at a sufficient distance to prevent contact during the rotatory movement. When the glass plate becomes charged, the positive electricity acts by induction on the neutral electricity of the conductor, decomposes it, and attracts the contrary electricity,—that is to say, the negative, which escapes by the points, by neutralizing equivalent quantities of the positive electricity of the glass. The positive electricity of the conductor is, on the contrary, repelled to the two metallic cylinders, where it accumulates. On one of these is placed a quadrant electroscope, furnished with a pendulum which shows the tension of the collected electricity. The glass is electrified in proportion as it rubs against the cushions, but the electricity disappears from it on passing before the points of the prongs. There are then only two sectors of the circle which are electrified; those which are seen in the figure protected by screens of oiled silk, which prevent loss through the humidity of the air. In order to cause the machine to work well, the air of the room must be dry and at a sufficiently high temperature; and before an experiment, the glass supports, which insulate the conductors, must be carefully wiped.

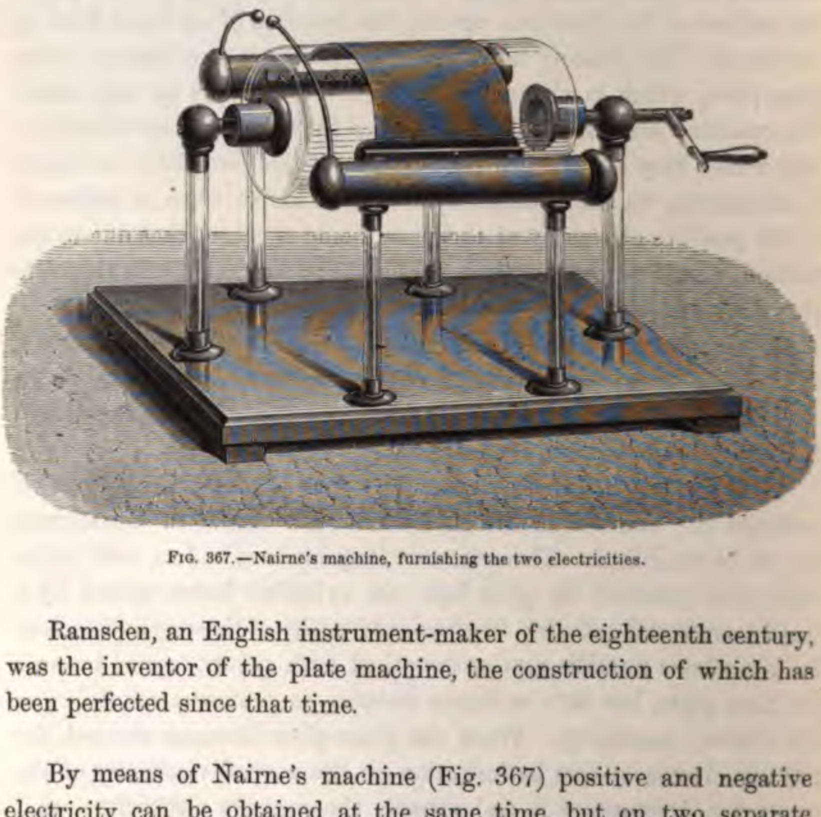

FIG. 367.—Nairne's machine, furnishing the two electricities.

Ramsden, an English instrument-maker of the eighteenth century, was the inventor of the plate machine, the construction of which has been perfected since that time.

By means of Nairne's machine (Fig. 367) positive and negative electricity can be obtained at the same time, but on two separate conductors. One of the conductors is furnished with points; it is electrified positively like those of the plate machine; the other conductor has a cushion, the friction of which against a glass cylinder determines the separation of the two electricities which form the neutral electricity of the system: a piece of silk also protects the surface of the glass from loss of developed electricity. Hence it follows that, whilst positive electricity accumulates on the glass, the negative is repelled to the cushion, and thence to the conductor. Only one of the two electricities can be collected: for this purpose, the conductor which contains the other electricity must be made to communicate with the ground, by means of a chain.

Van Marum invented an electrical machine which could be worked either like that of Ramsden, or that of Nairne; either positive or negative electricity could be collected on its conductors, or both at the same time.

If very dry mercury is shaken in a glass tube—in a barometer tube, for instance—we see, in the dark, a very faint light, which proves the production of a certain quantity of electricity; and, indeed, the glass tube then attracts light bodies. Friction of liquids against solids may also be employed as a method of electrization. But formerly we did not know how to utilize this action; a method, however, was discovered by chance in 1840, when a very efficient means of obtaining electricity by the friction of a jet of vapour mixed with minute liquid spherules, against a solid, was devised. Such is the principle of Armstrong's hydro-electrical machine, represented in Fig. 368.

A boiler, insulated by glass supports and filled with distilled water, is used to produce high-pressure steam; this escapes into the air through a series of jets, after being partly condensed in its passage through a box of water filled with wet packing, kept constantly moist.

The liquid drops, produced by the condensation of the vapour, rub with force against a layer of boxwood, which surrounds them, before penetrating into the jets by which they escape, and also against the sides of the jets, formed of the same wood. Electricity is thus developed in greater abundance as the pressure of the steam is higher: the boiler becomes charged with positive electricity, and the vapour with negative. To collect the latter, an insulated conductor, furnished with a series of points, is placed before the jets of vapour.

Hydro-electrical machines possess great power, and it is to be wished that they were more used. Among machines of this kind, that of the London Polytechnic Institution is said to be furnished

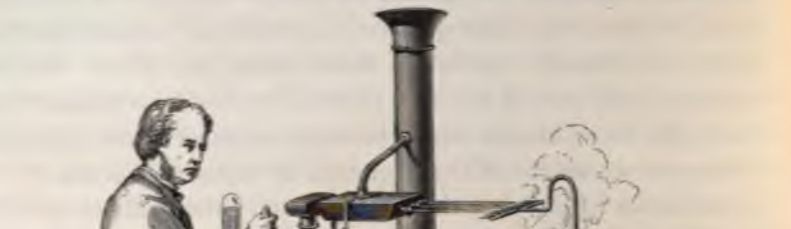

Fig. 368.—Armstrong's hydro-electric machine.

with forty-six vapour jets, and to give sparks sixty centimetres in length; that of the Sorbonne, in Paris, has eighty jets, and also furnishes continuous sparks of several decimetres in length.

We often employ in physical and chemical laboratories a more simple apparatus than that we have just described, which is competent to produce electricity rapidly; we allude to the *electrophorus.* It is composed of a disc of resin, sulphur, or caoutchouc, for instance, melted into a mould of wood or brass, and of a metal plate with rounded edges, furnished with an insulating handle. The resin, sulphur, or caoutchouc is electrified by rubbing it obliquely with a cat's skin;—it is thus charged with negative electricity; the metal plate is then placed on the electrified cake, and the neutral electricity of the metal is decomposed by induction, so that the lower surface in contact with the resin is electrified positively, and the upper surface negatively. On touching the upper surface with the finger, its negative electricity escapes to the earth; and if the metallic plate is then raised by the insulating handle, it remains charged with positive electricity in sufficient quantity to produce a spark.

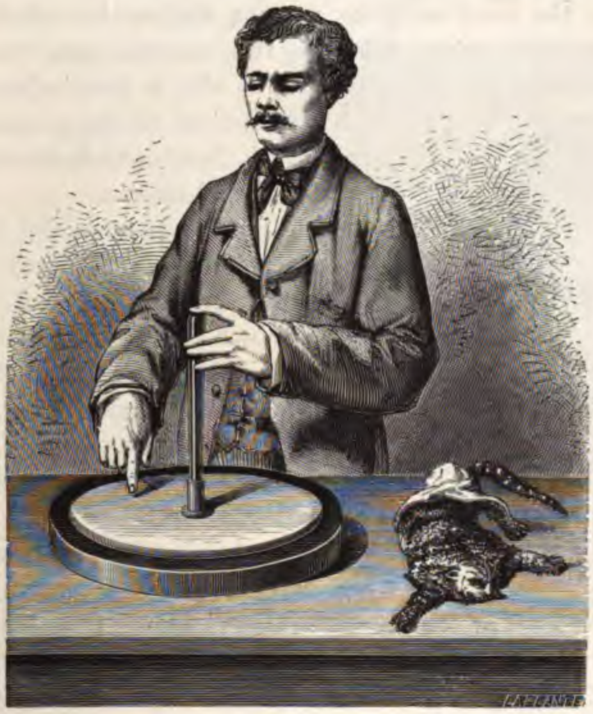

FIG. 369.—Electrophorus with resin cake.

We must remark that the electricity collected is not produced by the contact of the resin with the metal,—a contact which only takes place in a few points of the surface. The cake of resin remains, after the experiment, charged with negative electricity, so that the experiment can be repeated successfully several times and at long intervals. An electrophorus, placed where the air is very dry, preserves for whole months the electricity developed on its surface by friction.

Very curious lecture experiments can be made with the machines just described, which have been constructed in various forms. In mentioning some of the more interesting, we shall have occasion to study, in the most complete manner, the various effects of the mysterious agent whose existence, two centuries ago, was scarcely recognised; and we shall, moreover, be able to familiarise ourselves with explanations of the general phenomena which have formed the subject of the preceding chapters.

A metallic rod is suspended to one of the conductors of an electrical machine, and three bells are suspended from the rod, the two end ones by brass chains, that in the middle by a silk thread; this communicates with the ground by a metal chain. Lastly, between the bells, two little metallic balls (Fig. 370) are suspended by silk threads.

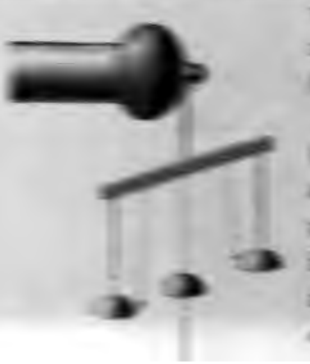

Fig. 370.—Electrical bells.

As soon as the machine is worked, the electricity of the conductor passes to the end bells, and the insulated balls are attracted, then repelled, as soon as they have established contact; the middle bell, which is in its natural or neutral state, when it is subjected to the influence of the two outside electrified bells, is charged with electricity of a contrary nature to that of the balls, and attracts them until they come in contact, and in its turn repels them. Then follows a series of successive blows and sounds, which are repeated as the conductor of the machine is charged. From this the name of *electrical bells* is given to this apparatus. Fig. 371 represents an apparatus invented by Volta for the purpose of explaining the movement of hailstones during storms: a glass bell-jar communicates with the ground by the plate on which it rests; a metallic rod, in contact by its outer extremity with the conductor of an electrical machine, passes into the bell-jar, and the other extremity is furnished with a metal plate. On the bottom of the bell-jar a number of pith balls are placed. As soon as the machine is charged, the electricity passes to the plate, attracts the balls, which are electrified by induction, and come into contact with the plate; they are then repelled, and fall to the bottom of the jar, where they discharge their electricity and return to their neutral state. These backward and forward movements continue so long as the conductor is charged with electricity; the phenomenon is known under the name of *electrical hail.* Sometimes the pith balls are replaced by little figures made of the same material, and this is called the puppet dance.

These three experiments prove, as we see, in an amusing form, the phenomena of electrical attraction and repulsion. We will now study the effects of electrical discharge between conducting bodies.

We have seen that if when an insulating body, a glass rod for instance, is electrified, we bring the finger near its surface, a spark, accompanied by a crackling sound, passes, while the glass remains electrified at its untouched portions: which is explained by the non-conductibility of the body employed. If, instead of an insulating body, a conductor is substituted, such as that of a charged electrical machine, the effect produced is much more energetic and the discharge more complete; moreover, the phenomena then observed depend on the manner in which the discharge is made,—that is to say, on the nature of the medium interposed between the electrified conductor and the body submitted to its influence.

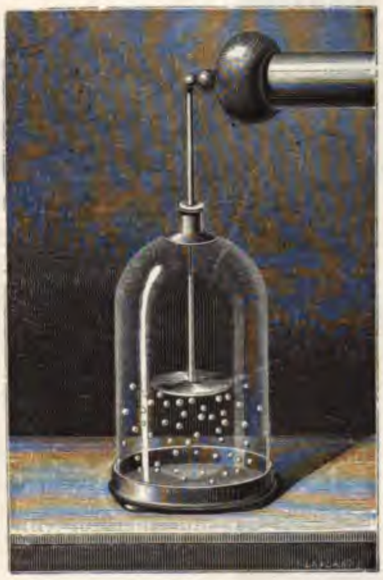
FIG. 371.—Electrical hail.

If the finger or any other part of the body is brought near the conductor of the machine, a spark is produced, and the sensation is stronger as the charge is greater. The quadrant electroscope placed on the conductor then falls to zero, showing that the electricity has been discharged;

but when the plate is turned in a continuous manner the sparks succeed each other with rapidity; the noise is a kind of crackling, and we feel a pricking sensation without any sharp shock. If the hand is not very near the conductor, the tension of the two electricities, as much that of the machine as that developed in the body by induction, becomes very strong; and when it is sufficient to overcome the resistance opposed by the distance to their recomposition, a long spark passes, and the shock shakes the whole arm. If, before turning the plate of the machine, a person is placed on an insulating stool, that is, a stool with glass supports, and he then places his hand on the conductor, he will be electrified at the same time as the latter; his body is then virtually a part of the conductor. Another person, not insulated, will then be able to draw sparks from his body, and each one will thus receive, at the same time, the shock which the discharge produces.

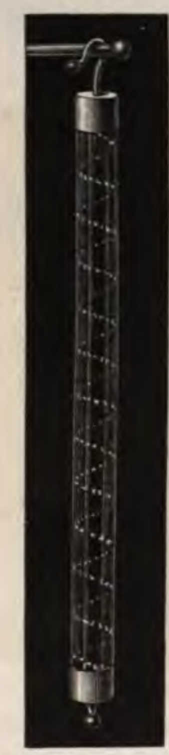

FIG. 372.—Luminous tube.

The luminous effects which the disengagement of electricity produces deserve a special and detailed study. We shall return to this hereafter, when we have reviewed the various methods of producing electricity; but we may now describe some experiments in which the production of the spark gives rise to singular actions of light.

On the surface of a glass tube a number of little lozenges of tinfoil are pasted in a spiral curve, a small space being always left between each of them. The extremities of the spiral and of the tube are two metallic rings, one connected with the conductor of the electrical machine, whilst the other communicates with the ground by a chain (omitted in the figure). As soon as the machine is charged, decomposition of the neutral electricity of the first tinfoil lozenge takes place by induction, then of the second by the first, and so on through the whole series. The small distance causes simultaneous discharges, and sparks appear at the same time along the entire spiral; the phenomenon lasts so long as the plate of the machine is turned (Fig. 372). This is the experiment of the *luminous tube*.

Similar luminous effects are obtained by means of a glass globe on the surface of which small tin lozenges are pasted so as to produce various designs. This is the *luminous globe* (Fig. 373). If on a rectangular sheet of glass, bands of tinfoil are pasted so as to form an uninterrupted series of parallel lines as in Fig. 374, a pattern of any form may be cut on this ground with a sharp point. A spark will appear at each solution of continuity when the extremities of the series are placed, the one in communication with the conductor of the machine, and the other with the ground; the figure drawn on the glass will be seen in the form of luminous lines. This is the *luminous square.* The magic pane only differs from the preceding by the irregular arrangement of the pieces of metal between which the electric spark appears: metallic filings are carelessly thrown on the surface of the glass covered with gum; when the pane is connected on one side with the machine, and the other with the ground, sparks appear, and trace out irregular and serpentine lines, their positions and figures changing every moment.

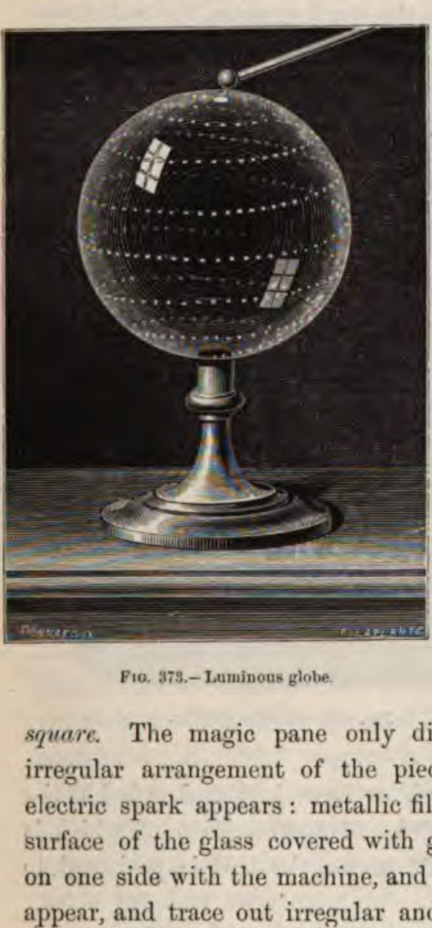

FIG. 373.—Luminous globe.

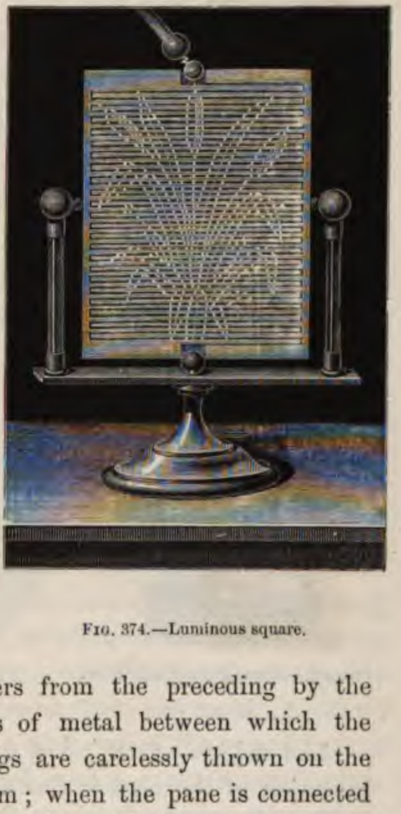

FIG. 374.—Luminous square.

In the experiments just described, the discharge takes place between two bodies charged with contrary electricities, separated from each other by an insulating medium, such as the air or glass. This recomposition of the two electricities is called a *disruptive discharge*, because it is accompanied by a violent movement of the molecules of the insulating body, which is proved by the following experiment:—

Two communicating tubes, of unequal diameter, the larger closed, and the smaller open at the top, contain a certain quantity of water (Fig. 375). In the large tube, two metallic rods, terminated by balls, are fixed, one to the base, the other to the upper part, and they communicate respectively with the ground, and with the conductor of the electrical machine. As soon as the spark appears, the water rises quickly in the open tube, then immediately regains its level. This shock is produced by the violent disturbance of the molecules of the air, and not by an expansion due to an elevation of temperature of the whole gaseous mass, as was at first believed by Kinnersley, the inventor of the apparatus. Nevertheless, it is still called Kinnersley's thermometer.

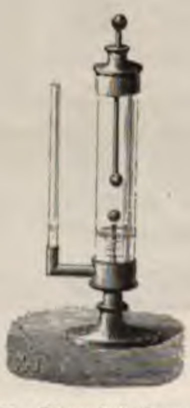

FIG. 375.—Kinnersley's thermometer.

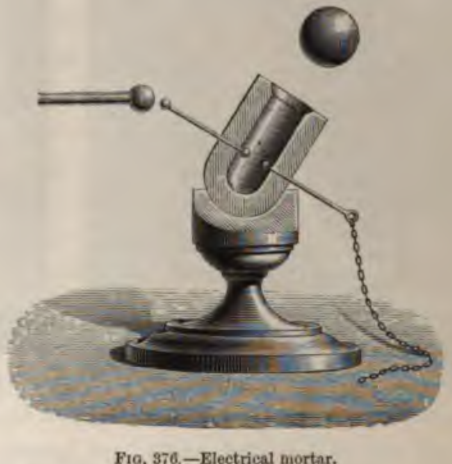

FIG. 376.—Electrical mortar.

The sudden expansion of which we have just spoken led to the invention of the electric mortar (Fig. 376), the action of which is easily understood; when the spark passes, the ball is projected to some distance.

For the present, we will confine ourselves to these few experiments. Those of our readers who possess apparatus may easily repeat them.

CHAPTER III.

LEYDEN JAR.—ELECTRICAL CONDENSERS.

The experiments of Cuneus and Muschenbroeck; discovery of the Leyden jar—Theory of electrical condensation; the condenser of Æpinus—Jar with moveable coatings—Instantaneous and successive discharges—Leichtenberg's figures—Electric batteries—The universal discharger—Apparatus for piercing a card and glass—Transport and volatilization of metals; portrait of Franklin—Chemical effects of the discharge; Volta's pistol—Fulminating pane.

CUNEUS, a pupil of Muschenbroeck, a celebrated physicist of the last century, endeavoured one day to electrify water contained in a wide-necked bottle. To effect this, he held the bottle in one hand, after having passed a metal rod suspended on the conductor of an electrical machine into the liquid. When he imagined that the water was sufficiently charged with electricity, he lifted up the iron wire in contact with the conductor with one hand, without removing the other from the bottle, and he immediately felt a violent shock which filled him with surprise. Muschenbroeck repeated the experiment of Cuneus, but the shock which he received caused him such fear that on communicating this fact (which was unknown among electrical phenomena at that time) to Réaumur, he told him that no inducement, not even the offer of the crown of France, would induce him to receive another shock. Other physicists, however, were less timid. Allaman, Lemonnier, Winckler, and the Abbé Nollet, varied the experiment in many ways, and science was enriched with a new electrical instrument; the *Leyden jar,* thus named from the place where the experiment was first made, in 1746. The following is the way in which this apparatus is now constructed :—

A bottle made of thin glass has its bottom and three-quarters of its height covered with a metallic coating, generally of tinfoil; this is

called the outer coating or armature of the jar. The interior c
or armature is sometimes a metal lining the inside of the jar.
times the bottle is filled with a quantity of gold leaves or tins
Muschenbroeck's jar, water was the conducting body. Lastly, a
rod, with a hook at one end, terminated above by a little b
passed through the cork which closes the neck, and commun
with the inner coating of the bottle.

To charge the Leyden jar it is suspended by its rod
conductor of an electrical machine, care being taken to establi

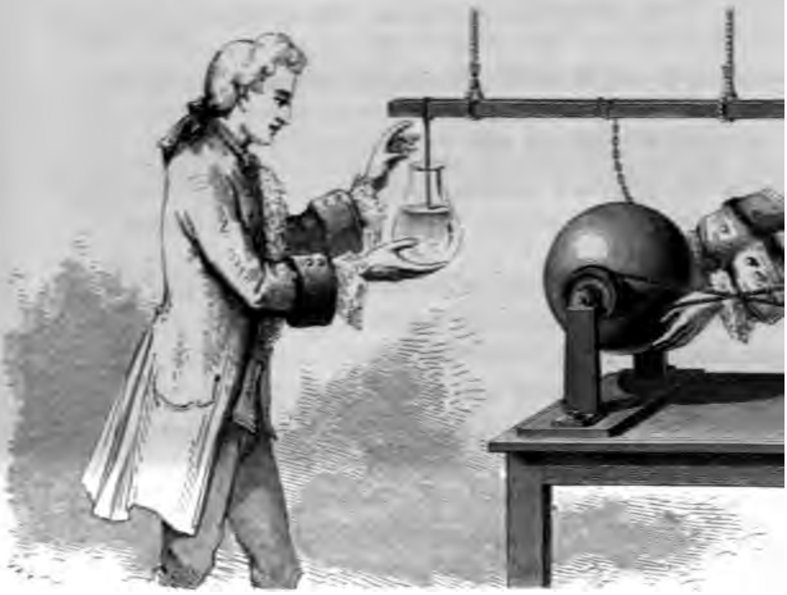

Fig. 377 – Cuneus' experiment (the Leyden jar).

means of a metal chain, communication between the ground a
outer coating. It can also be held in the hand by the latte
then presented to the conductor of the machine.

When the bottle is charged with electricity, if the outer and
coatings are connected by a conducting body, a discharge takes
accompanied by a spark and explosion. If the apparatus is h
one hand and the other is placed near the ball, the discharge wi
through the arms and body, and we receive the shock which frig
the first operators so much. If several persons hold each ot
the hand, two and two, the first of the series holding the bott

presenting the rod to the last one, as soon as contact is made, the shock will be felt at the same time by all. Nollet showed this experiment before Louis XV.; three hundred French guards formed the chain and simultaneously received the shock produced by the instantaneous discharge of the Leyden jar.

Before describing the many curious experiments which may be made with this apparatus, we will endeavour to give the theoretical explanation of the double phenomena of the charge and discharge of the Leyden jar. We may first observe that the apparatus must be composed of two conducting bodies, the exterior and interior metallic coatings, and of an insulating body, which separates them—the glass bottle. When the hook is suspended on the electrified conductor of a machine, the electricity of the latter passes to the surface of the inner coating, which is thus charged with, say, positive electricity. This electricity decomposes the neutral electricity of the outer coating by induction, attracts the negative electricity to the surface of the glass, and repels the positive electricity to the ground, through the medium of the body of the operator or through the metallic chain. Thus two charges of contrary electricities are brought together, which the interposition of the insulating glass prevents from combining. If the union of these two electricities is desired, we unite them by any conductor whatsoever, and their combination is accompanied by explosion and a spark. Hitherto it has not appeared necessary to adopt any other explanation: the preceding *rationale* also accounts for the phenomena of electrical induction, but we shall see that it is, in reality, insufficient.

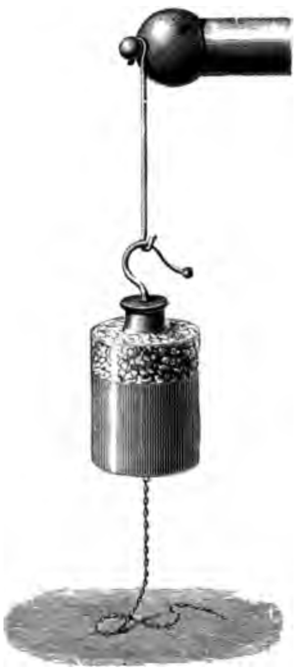

FIG. 378.—Charging the Leyden Jar.

First, the size of the spark and the violence of the shocks indicate in this case an electrical tension of an unusual energy; the accumulation of the two electricities in such quantity no longer seems in proportion to the small dimensions of the conductors which compose the apparatus. The following is a fact which also requires explanation:—When a Leyden jar is discharged and it is placed aside for a while, it will be found somewhat charged without having been again placed in communication with the source of electricity. A second spark will appear, but weaker than the first. This is called a *secondary discharge.* It is evident, therefore, that the Leyden jar accumulates a larger quantity of electricity than that which can be obtained by the use of simple insulated conductors. For this reason it is named, in common with all similar apparatus, a *condenser.* Let us now inquire whence comes this power of accumulation, and what new phenomena intervene to produce it. The theory of electrical condensation, first propounded by Æpinus, will enable us to understand this and the cause of the preceding phenomena.

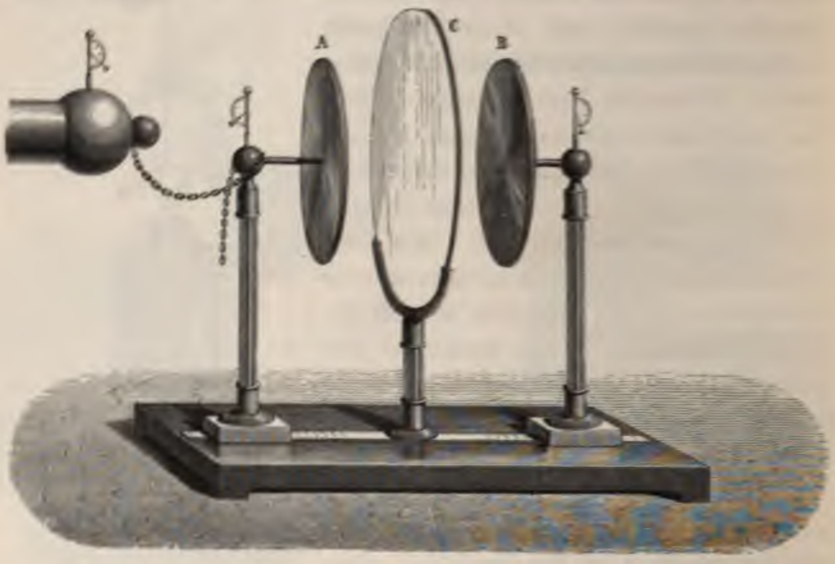

FIG. 379.—The condenser of Æpinus.

The condenser invented by this physicist is represented in Fig. 379; it consists of two insulated metallic plates A, B, mounted opposite each other on glass supports, and separated by a glass disc. They move in a groove, and can thus be brought as near together as may be desired, or, at least, with only the thickness of the insulating disc between them. Quadrant electroscopes are fixed on the metallic rods which support the two plates.

Let us suppose that the plates are at first some distance from each other, and let A be put in communication with the electrical machine. It becomes charged with positive electricity, the tension ending by being equal to that of the source, and its electroscope diverges. Moreover, this tension is nearly equally distributed over the two sides of the plate A (Fig. 379). Let us now approximate the plates A and B; the latter will be charged by induction with negative electricity on the side facing the glass disc, and positive electricity on the other side, and its electroscope will also diverge; but if the communication of A with the electrical machine is discontinued, the attraction of the negative electricity of B for the positive electricity of A goes on increasing on the anterior side of the plate, and the electroscope of A will again fall to zero. If B is now put in communication with the ground, the positive fluid escapes, a fresh decomposition is made, and the negative electricity is accumulated on the anterior side of this plate, in greater quantity than before; and by reaction, the tension on the plate A has become stronger on the anterior side to the detriment of the posterior face, which returns to its normal condition. Again, when the communication of A is re-established with the electrical machine, a fresh quantity of positive electricity passes to A, and the condensation will still increase (Fig. 380). The same series of operations continued from time to time will produce a maximum condensation on one or other of the plates. It will be now easily seen that the condenser of Æpinus and the Leyden jar only differ in form, and

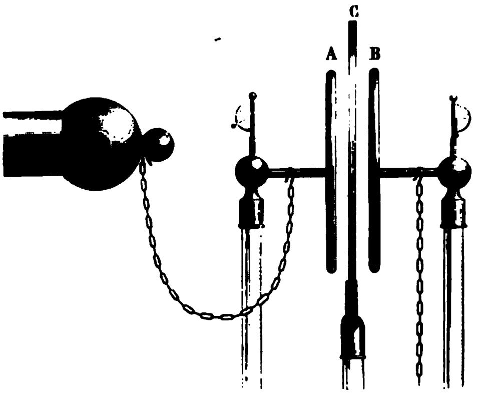

FIG. 380.—Charging the condenser of Æpinus.

that the phenomena which can be observed in
the same manner in the other. Let us inqui
glass disc plays in the experiment. Both tl
prove that a layer of any other insulating su
layer of air interposed between the conductors
phenomena; but as the air presents a more fee
glass to the opposite tensions of the contrary el
on the sides opposite the conductors, only a fee
be obtained. Hence the necessity of interp
body, like glass or resin.

Moreover, according to the numerous ex
and Matteucci, it has b
two charges, positive and
accumulated on the surf
the glass and with the
densers, but that the elec
trate the glass to a cert
has been proved by me
with moveable coatings f
as represented in Fig.
the whole jar, it is place
inner coating is raised by
then the glass jar, and it
there is very little electr
whilst the jar itself is stro
over, after having discharg
they are again replaced th
as bright as if the partial discharges had n
penetration of the electricity to a certain dep
body of the condensers explains, in a sat
secondary discharges of the Leyden jar; it sh
metallic coatings also perform the part of plac
of the glass in easy communication, and in vi
bility, the discharge is made instantaneously, a

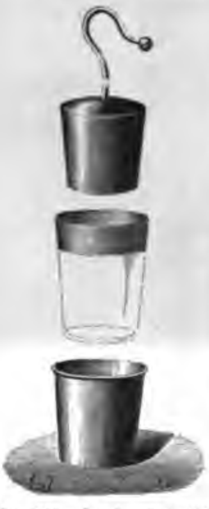
Fig. 381.—Leyden jar with moveable coatings.

We will now describe some curious exper
easily made with this condenser.

The discharge of the Leyden jar can be m
gradually, without the danger of any shock to

The instantaneous discharge is made by means of a discharger; this consists of two metallic rods, turning on a common joint, and furnished with glass handles (Fig. 382). The handles are taken in the hands, and the two metal balls which are at the ends of the rods are placed, one near the ball of the inner coating, and the other touching the outer coating of the Leyden jar; the discharge is made through the branches of the discharger. Successive discharges are sometimes made with the bell Leyden jar, shown in Fig. 383. The insulated pendulum which surmounts a bell fixed on a metallic stand, and communicating with the exterior coating, is successively attracted and then repelled by the electricity of the interior coating, afterwards to undergo the same actions from the other bell. At each contact, the ball takes away a part of its electricity, alternately from the one and from the other of the two coatings. The jar is thus gradually discharged. Sometimes the ball of the pendulum is made in the form of a spider, with legs made of pieces of silk.

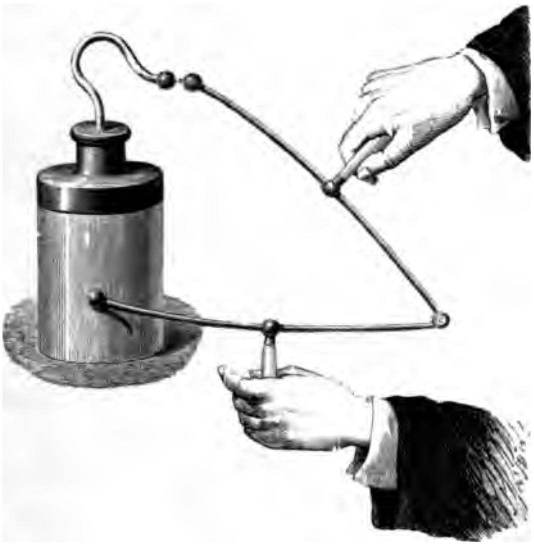

FIG. 382. – Instantaneous discharge of a Leyden jar by means of the discharger.

Experiments with the sparkling jar (Fig. 384) prove that, in the instantaneous discharge, the electricity comes from all parts of the glass to converge towards the point where the reunion of the accumulated electricities on the two coatings takes place. The exterior coating is formed, as in the magic square, of fragments of metal filings, or tinsel, fixed on a layer of gum; and a band of metal which comes out at a little distance from the outer coating is fixed to the interior coating. When the jar is sufficiently charged, lines of fire will be seen to wind about its surface, starting from the point where the discharge begins (Fig. 384). We have just seen that the Leyden jar is charged with contrary electricities on the two sides of the coatings; a German physicist, Leichtenberg, devised a very interesting experiment to prove this. He took a cake of resin, similar to that of the electrophorus, then charged a Leyden jar, and traced on the cake with the ball some figure, the letter G for example; he then replaced the jar, and taking hold of it again, this time by the hook, he traced another design on the cake with the lower edge of the jar. He next projected a cloud on the surface of the cake by means of bellows filled with a powder formed of minium and sulphur; the minium was seen to place itself on the parts touched by the ball,—that is to

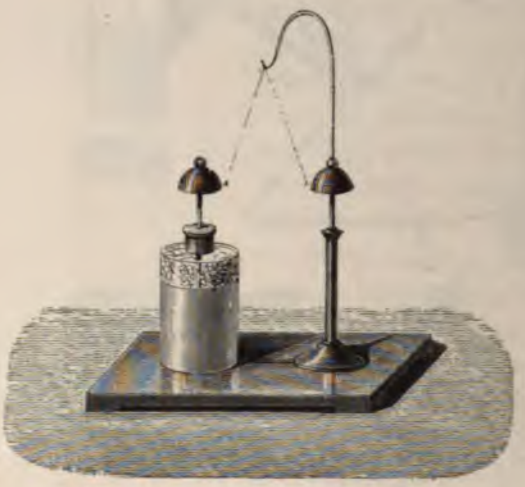

FIG. 383.—Successive discharges of a Leyden jar. Chimes.

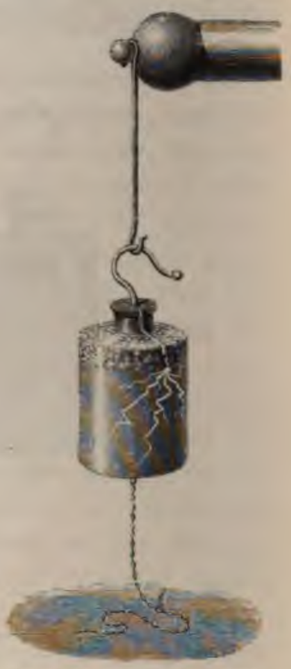

FIG. 384.—Sparkling Leyden jar.

y, negatively electrified, whilst the sulphur attached itself to the rts charged with positive electricity. Figs. 385, 386, and 387 are c-similes of Leichtenberg's figures, which M. Saint Edme, Demonrator of the Physical Lectures at the Conservatoire des Arts et étiers, has kindly prepared for this work. The two drawings, sitive and negative, obtained by the contact of the resin with the

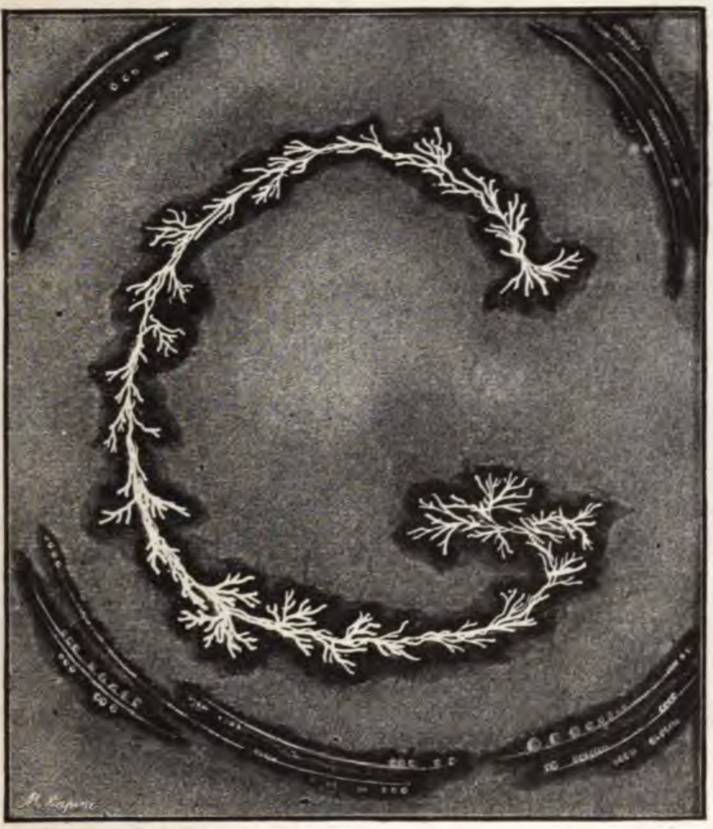

FIG. 385.—Leichtenberg's figures. Distribution of the two kinds of electricity.

vo coatings, are distinguished not only by the colour of the powders hich cover them, but also by the form of the singular ramifications hich the contrary electricities have traced on the resin.

To obtain stronger effects we must increase the size of the eyden jar.

The glass jar, with a large aperture, which allows tinfoil similar to the outer coating to be pasted within it, is called an *electrical jar.* Several jars placed together, as shown in Fig. 388, form a battery. All the interior coatings are then connected together by means of metallic rods, proceeding from the ball of each of them, and radiating towards the largest ball of the centre jar; the latter ball is put in communication with the conductor of the electrical machine, when the battery is to be charged. The outer coatings are connected together by contact with the tinfoil, with which the inside of the box is covered, and which communicates with the ground by a metallic chain.

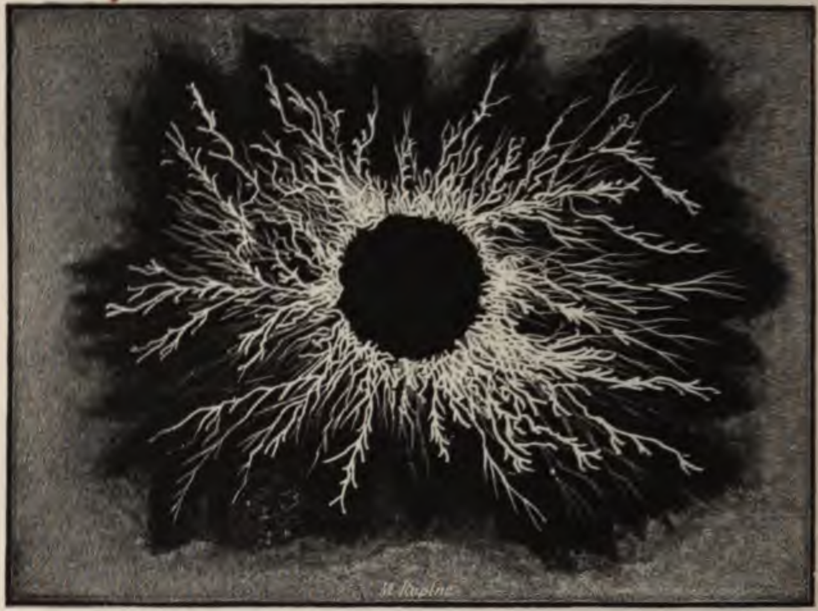

FIG. 386.—Leichtenberg's figures. Distribution of the positive electricity.

The electric charge which these powerful condensers accumulate on their coatings is very considerable, and some time is required to furnish them, by ordinary machines, with the electricity they are capable of condensing. The operation can be made more rapid by dividing one battery into several batteries, each enclosing two or three jars, and causing them to communicate, two and two, by rods uniting the interior coatings. The discharges of electrical batteries obviously become more dangerous as the jars increase in surface and number. A battery of six elements of mean size would give very strong shocks, sufficient indeed to kill such animals as rabbits and dogs. Precautions must be taken when they are discharged; for this purpose the *universal discharger* (Fig. 389) is used, as well as for numerous other experiments. This apparatus is formed of two brass rods, each terminated at the one end by a ring, to which a chain can be attached, and at the other by a knob. The rods are insulated on glass supports, and are moveable on a joint. The knobs are directed towards a stand, on which the body through which the discharge is to be passed is placed. One of the chains communicates with the ground, and the other with an ordinary discharger, by which the central knob of the electrical battery can be touched without danger.

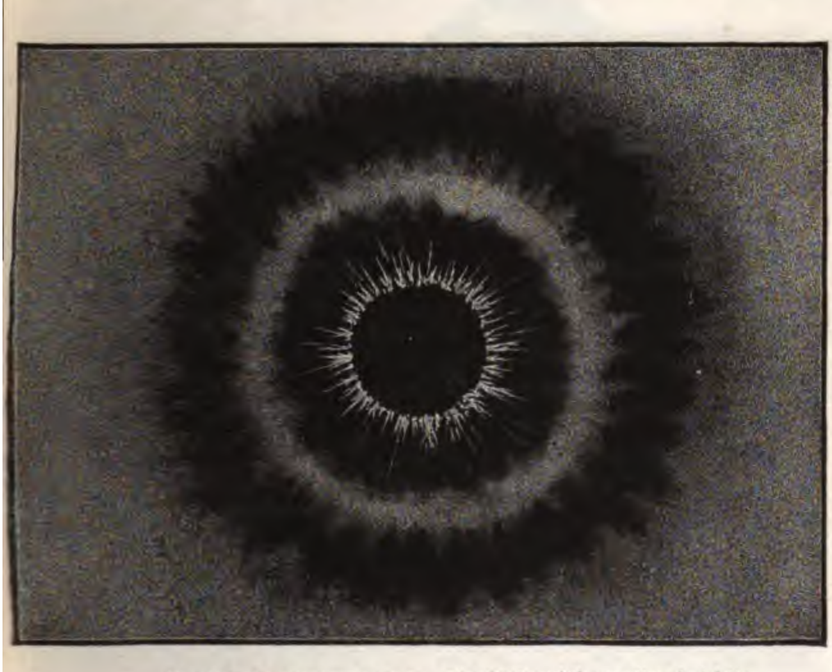

FIG. 387.—Leichtenberg's figures. Distribution of the negative electricity.

We will conclude this chapter with the description of some experiments which show the different mechanical and physical effects of electricity accumulated in condensers.

In the experiments of the electric mortar and Kinnersley's thermometer, we have already seen the mechanical effects which the disruptive discharge can produce. The violent displacement of the molecules of the body interposed between the two conductors is rendered still more manifest in the apparatus for perforating a card, or a sheet of glass.

A card is placed between two points with metallic conductors separated by a glass rod (Fig. 390). A charged Leyden jar is then held in the hand, having its exterior coating in communication with one of the conductors by a metallic chain; the knob of the inner coating is now brought near the other conductor. The discharge takes place through the card, which is found to be pierced with a hole between the two points. We do not know why the hole is nearer the negative point than the positive, in the open air, whilst this is not the case when the experiment is made *in vacuo;* but such is the case.

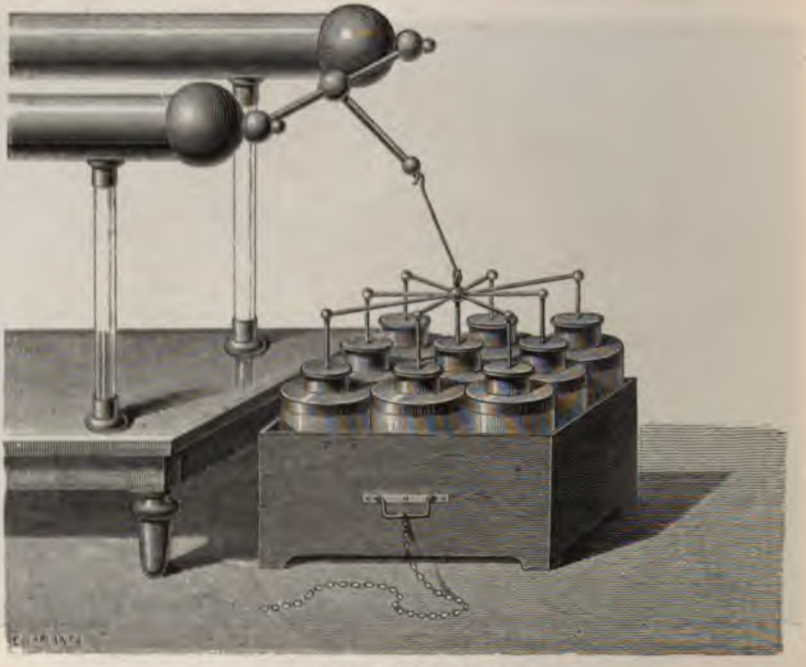

Fig. 388.—Battery of electrical jars.

A piece of glass of 1 or 2 millimetres in thickness can be pierced in the same manner, by placing it horizontally between the two points (Fig. 391); care must be taken, however, to cover each of the metallic points with oil, to prevent the electricity from being diffused over the surface of the glass. After the discharge, a small round hole is found in the glass; and the glass in its path has been pulverized by the passage of the electricity. In order to make this experiment succeed it is necessary to use a powerful battery, but even when the discharge is not strong enough to pierce the glass it is found to be altered and rough at the point where the spark appeared.

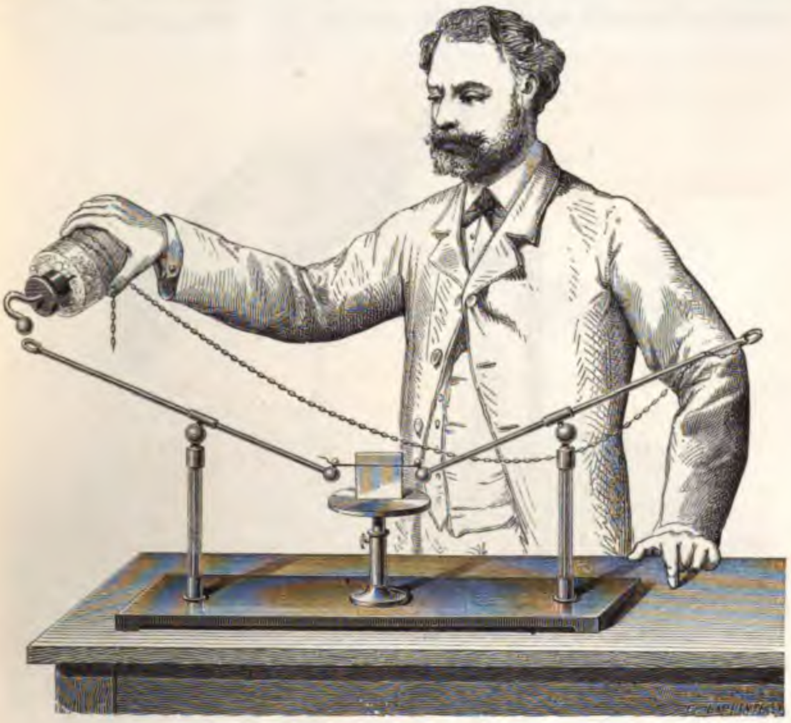

FIG. 389.—Universal discharger.

The calorific effects of the electrical discharge are not less interesting than the mechanical effects. If the two balls of the universal discharger are united by a very fine metallic wire, of silver for example, the wire becomes incandescent, and it is melted and vaporized if the electrical charge is sufficiently strong. With the powerful batteries of the Conservatoire des Arts et Métiers, iron wires several metres in length can be melted. Wires of the same diameter and the same length require very different electrical charges to melt them: iron, lead, and platinum melt more easily than gold, silver, and especially copper. Fusion is caused more readily if the discharge takes place in air, than if it is made *in vacuo.* If a gilded silk thread is placed between the balls of the universal discharger, the discharge melts the gold and leaves the silk intact; and the particles of the volatilized metal can be collected on a white card, on which the thread may be placed before the experiment. A blackish spot will be seen on the card, formed of very fine volatilized powder of gold. By working with different metals, spots of various colours can be obtained, and, if the metals used are oxidizable at very high temperatures, the markings obtained are formed of metallic oxides, reduced to impalpable powder. In the last century, Van Marum made some very beautiful experiments on the transport of metals by the electrical discharge. Fusinieri, having passed a discharge between two balls, one of gold and the other of silver, observed that the first was silvered and the second gilded round the points between which the spark appeared. It is probable that the phenomena of which we have just spoken are complex, and are due, at the same time, to the rise of the temperature

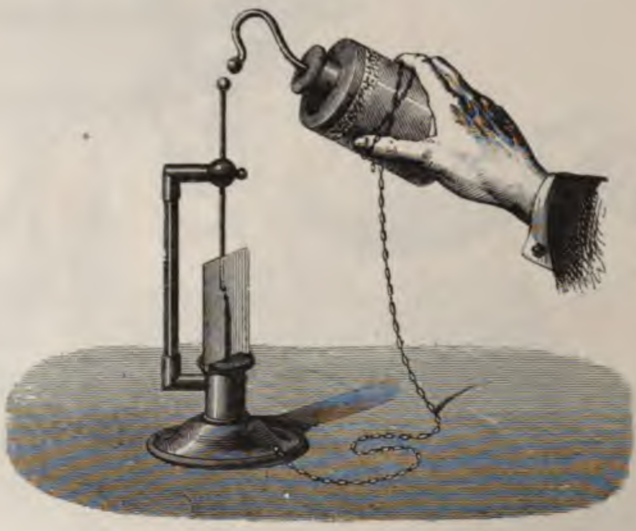
FIG. 390.—Experiment of perforating a card.

produced by the discharge, and to the mechanical transport of the molecules.

This property has been made of use to obtain metallic prints reproducing various drawings. In lectures, the experiment of *Franklin's portrait* is sometimes made. Fig. 392 shows a thick sheet of paper in which the portrait of the illustrious physicist is cut; layers of tin are pasted on each side of the sheet, which is also covered above with gold leaf, and below with a piece of white silk. After having pressed down on the gold leaf the parts of the paper which are above and below the portrait, the whole is placed in a press (Fig. 393), the screws tightened to render the contact perfect, and the press is itself placed on the stand of the universal discharger. When the balls of the discharger are in contact with the tin bands which extend laterally beyond the press, the discharge is passed through it, and the volatilized gold leaf produces a blackish impression on the silk, which reproduces all the cuttings, and the drawing is thus, so to speak, printed by electricity.

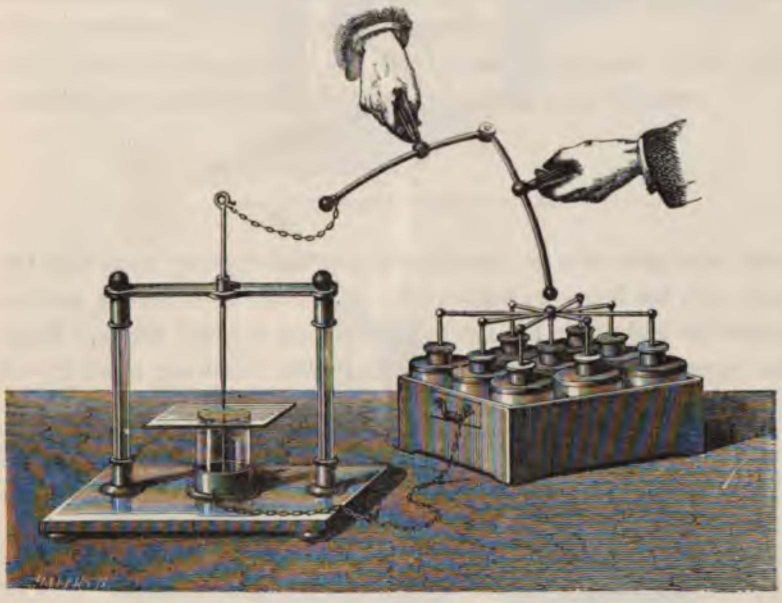

FIG. 391.—Experiment of perforating glass.

The fusion of metallic wires is a certain proof of the rise of temperature which accompanies electrical discharges, when they take place through a conductor. Disruptive discharges, that is to say, those made through an insulator like air, with the production of a spark, also give rise to calorific effects, although on receiving the spark with the finger no heat is felt. Combustible materials, such as gunpowder and ether, are ignited by sending a spark through them. This experiment was formerly made in the following manner:—A person mounted on an insulating stool, with one hand touched the conductor of an electrical machine, while with the other he presented the point of a sword at a short distance from a saucer full of ether held by another person. The liquid ignited immediately on the passage of the spark. Watson succeeded in setting fire to ether by means of a spark issuing from a piece of ice.

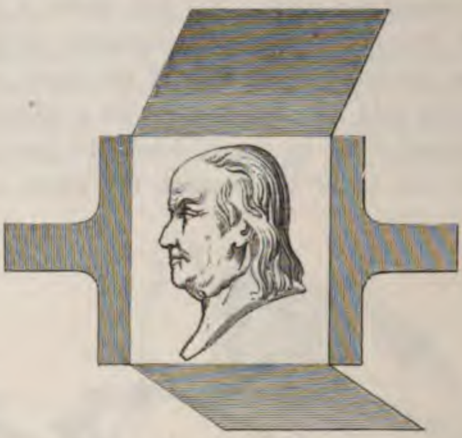

FIG. 392.—Franklin's portrait experiment.

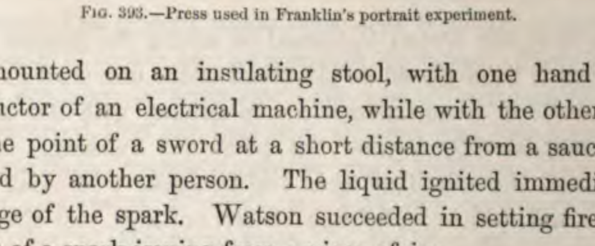

FIG. 393.—Press used in Franklin's portrait experiment.

The electrical spark also produces chemical effects of great interest. If it is passed through a mixture of explosive gases, oxygen and hydrogen, for example, the explosion is instantaneous. On this fact is based the construction of Volta's pistol. Figs. 394 and 395 represent a section and exterior view of this little apparatus; it consists of a metal sphero-cylindrical vessel, closed with a stopper and filled with a mixture of hydrogen and oxygen; a brass rod terminated by two knobs crosses the lower part of the cylinder, from which it is insulated by a glass tube. The apparatus being in communication with the ground, the exterior knob of the conductor of an electrical machine is brought near; the combination of the two gases then takes place with explosion, and the stopper is forcibly ejected to a distance.

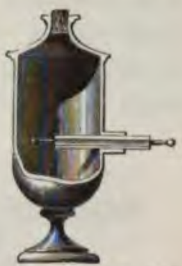

FIG. 394.—Volta's pistol. Interior view.

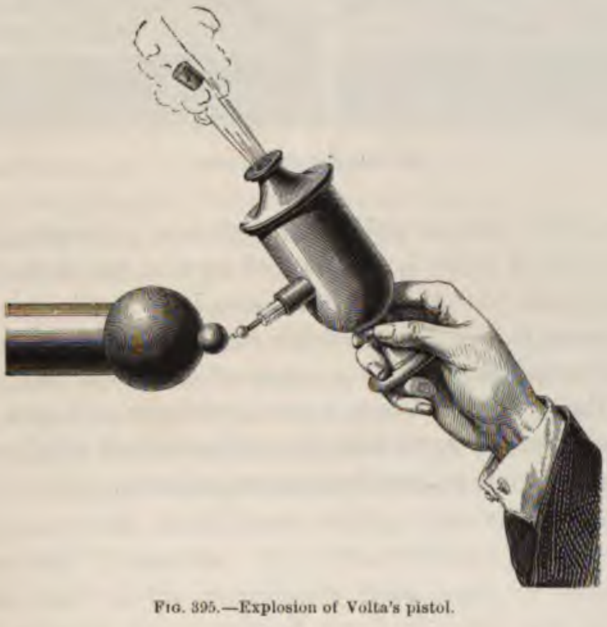

FIG. 395.—Explosion of Volta's pistol.

The electrical spark produces a number of chemical reactions, among which we may mention the formation of nitric acid from oxygen and nitrogen, the decomposition of water and of ammonia.

We have already alluded to the effects of the discharge when it passes through the organs of man and animals. The shocks are much stronger, and they affect a larger portion of the body, when they proceed from more powerful charges; and we have said that it is dangerous to receive the charge of a battery formed of even a small number of Leyden jars. By means of the condenser known as the *fulminating pane*, an experiment can be made in which the shock which the discharge produces has a singular and amusing effect.

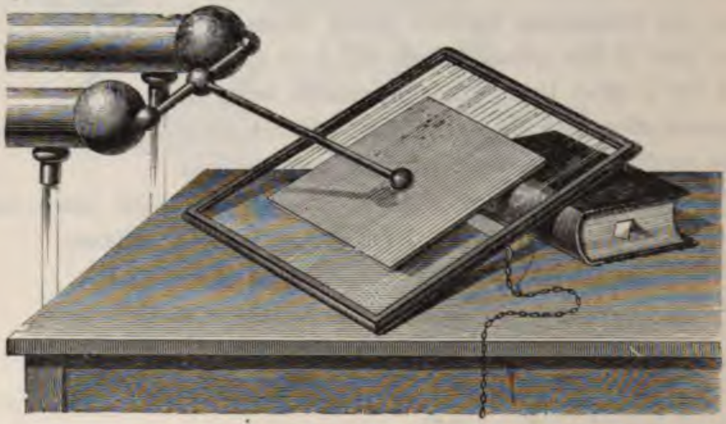

FIG. 396.—Fulminating pane.

The fulminating pane is nothing more than a rectangular plate of glass, each side of which is covered with tinfoil: one of the coatings is insulated, and the other communicates by a small plate with a wooden frame, thence, by a metallic chain, with the ground. The other leaf communicates with a source of electricity, and the condenser is thus charged; if, now, a person wishes to pick up a piece of money placed on the upper leaf, he receives a shock which contracts his fingers, and prevents him from taking hold of it.

CHAPTER IV.

THE PILE OR BATTERY.—ELECTRICITY DEVELOPED BY CHEMICAL ACTION.

Experiments of Galvani and discoveries of Volta; Condensing Electrometer—Description of the upright pile—Electricity developed by chemical actions—Theory of the Pile; electro-motive force; voltaic current—Electricities of high and low tension—Couronne de tasses; Wollaston's pile; helical pile—Constant-current piles; Daniell, Bunsen, and Grove elements—Physical, chemical, and physiological effects of the pile—Experiments with dead and living animals.

IN the experiments hitherto described, the electricity has been developed on the surface of the bodies by a mechanical means; such as friction, pressure, and cleavage. These were indeed the only methods of generating electricity that were known at the end of the last century, when a fortunate occurrence suddenly revealed to physicists a new method of producing the mysterious agent, and brought to light a series of discoveries of the greatest interest, not so much perhaps in reference to pure science as to practical applications. Two great names are connected with the origin of the discovery which added so much to the science of electricity—Galvani and Volta.

Galvani, a learned doctor and Professor of Anatomy in the University of Bologna, was one evening, in the year 1780, very busy in his laboratory with some friends, making experiments relative to the nervous fluid of animals. At a short distance from an electrical machine used in the experiments there were, by accident, some freshly skinned frogs destined for broth, and one of Galvani's assistants "inadvertently brought the point of a scalpel near the internal crural nerves of one of these animals; immediately all the muscles of the limbs appeared to be agitated with strong convulsions. Galvani's wife was present; she was struck with the novelty of the phenomenon, and she thought that it concurred with the passing of a spark."[1] She at once told her husband, who hastened to prove this curious fact, and discovered that the muscular contractions of the frog did indeed take place whenever a spark was made to pass, whilst they ceased if the machine was not in action.

To the Bolognese doctor this observation was the starting-point of numerous experiments, by which he sought to prove the identity of the nervous fluid of animals with electricity. In 1786 he was still continuing this research; and wishing one day to see if the influence of atmospheric electricity on the muscles of frogs would be the same as that of the electricity produced by machines, he hung a certain number of skinned frogs to the balcony of a terrace of his house. The lower limbs of these animals were hooked on the iron of the balcony by means of a copper wire, which passed under the lumbar nerves. Galvani noticed with surprise that whenever the feet touched the balcony the limbs of the frogs were contracted by sharp convulsions, although at that time there was no trace of a thunder-storm, and consequently no electrical influence in the atmosphere. These facts suggested to Galvani the idea that there existed a kind of electricity peculiar to animals, inherent in their organization; and that "the principal reservoirs of this animal electricity are the muscles, each fibre of which must be considered as having two surfaces, and as possessing by this means the two electricities, positive and negative." Hence, he associated the muscular contractions observed in frogs and other animals with the shocks given by the discharge of the Leyden jar.

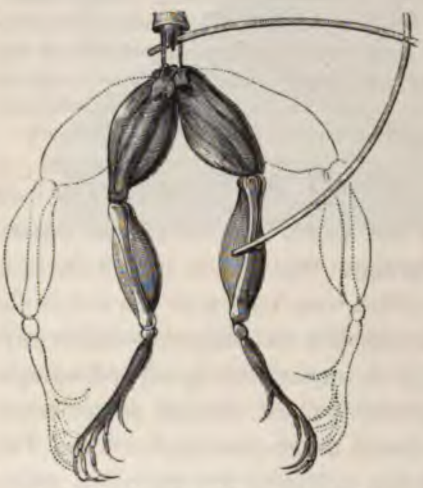
FIG. 397.—Contraction of the muscles of a frog. Repetition of Galvani's experiment.

Alexander Volta, then Professor at Pavia, repeated Galvani's experiments, but without adopting his explanations. According to him, the electricity developed is of the same nature as that produced by ordinary electrical apparatus: it is the contact of heterogeneous metals which gives rise to the production of electricity, one metal being charged with positive electricity and the other with negative electricity, which combine on passing through the conducting medium of the muscles and nerves.

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[1] P. Sue, "Histoire du Galvanisme."

A discussion was carried on between these two celebrated physicists, a controversy honourable to both and particularly profitable to science, which by this means was enriched by a number of new facts. The invention of the wonderful apparatus which received the name of the Voltaic pile, at last secured the adoption of the theory of the Pavian professor; although now Galvani's hypothesis on the existence of animal electricity has partly been established, and Volta's ideas have been greatly modified. This is not the place to give the history of the controversy we have just mentioned, nor of the various researches which accompanied and followed it: we must rather confine ourselves to the description of the principal phenomena which relate to this branch of electricity, and to an account of the explanations now given of them.

We have seen that Volta thought that the putting in contact of two different metals was sufficient to produce electricity; and for the purpose of studying the circumstances of this production he invented an electroscope more sensitive than the gold-leaf electroscope, which consists of this latter with the conducting rod surmounted by a condensing plate (Fig. 398). Taking a plate formed of two pieces of copper and zinc soldered together, he placed the copper in contact with one of the condensing plates, whilst, with the finger, the other plate was put in communication with the ground; as soon as the communications were broken, the gold leaves diverged, and he found the lower plate to be charged with negative electricity. Volta concluded from this experiment that the simple contact of the two metals was sufficient to develop negative electricity on the copper, the presence of which was shown by the electrometer; and positive electricity on the zinc, which escaped into the ground through the body of the observer. He was confirmed in this idea by the fact, that after many attempts, at first unsuccessful, he proved the presence of positive electricity in the zinc on touching the plate of the apparatus with that metal. Indeed, he deceived himself; for to obtain this result, he was obliged to interpose between the zinc and the copper plate a piece of cloth soaked in acidulated water. In these various observations Volta did not take into account the contact of the fingers, always more or less damp, with the zinc, a very oxidizable metal; nor, in the second experiment, the influence of the acidulated water on the same metal. However this may be, he admitted that the contact of two dissimilar metals, and of any two heterogeneous bodies in general, gives rise to the development of a force which he called *electro-motive force*, because it is opposed to the combination of the opposite electricities produced on each of these bodies by the contact of their surfaces. Although these theoretical views are now known to be inexact, the fact which they were adduced to explain was real; and this suggested to the illustrious physicist the construction of an apparatus which has been justly considered as the chief discovery of physical science in modern times—we allude to the pile which bears his name, the Voltaic pile or battery, invented in 1800.

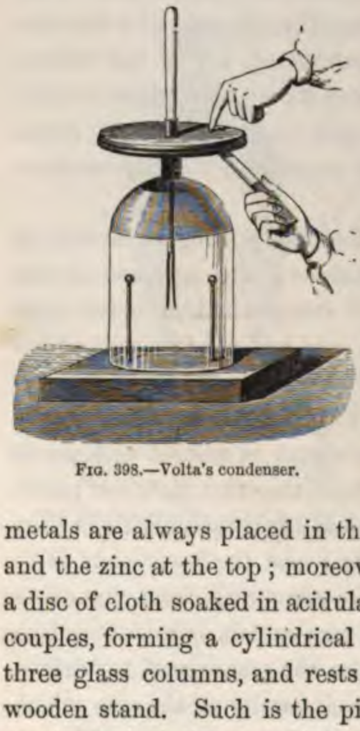
FIG. 398.—Volta's condenser.

The construction of this apparatus is as simple as it is wonderful.

Two superposed discs, one of copper and the other of zinc, form what Volta called an *electro-motive couple;* a certain number of these couples are placed one on the other, in such a manner that the two metals are always placed in the same order, the copper at the bottom and the zinc at the top; moreover, each pair of couples is separated by a disc of cloth soaked in acidulated water. The entire number of these couples, forming a cylindrical column or pile, is supported between three glass columns, and rests on an insulating glass disc fixed to a wooden stand. Such is the pile as constructed by Volta and as it is constructed at the present day, with the exception of a modification which will be spoken of presently. The following are some of its properties:—From end to end of the cylindrical column, each couple is charged with electricity—positive electricity on the zinc, and negative on the copper—of which we may assure ourselves by the aid of a condensing electrometer. But the electrical tension varies according to the distance of each couple from the extremities of the pile: at the centre this tension is *nil;* thence the negative tension increases to the lower couple, and the positive tension increases equally to the top couple. The greater the number of elements or couples, the greater the tension of the electricity at the extremities of the pile.

In the pile constructed by Volta, and arranged as we have said, a copper disc forms the lower extremity, whilst the upper is terminated by a zinc disc. These two discs are omitted in the pile-columns as constructed in the present day, for the following reason:—Volta believed that the real electro-motive couple was the assemblage of the two metals, zinc and copper, in contact, and that the disc of damp cloth served simply as a conductor. It has since been proved that the electro-motive force is produced at the contact surface of the damp cloth and the zinc, under the influence of the chemical combination of the metal and the acid; the true couple is therefore formed of the zinc and copper, separated by the liquid with which the cloth is soaked. Therefore the copper disc of the lower extremity, and the

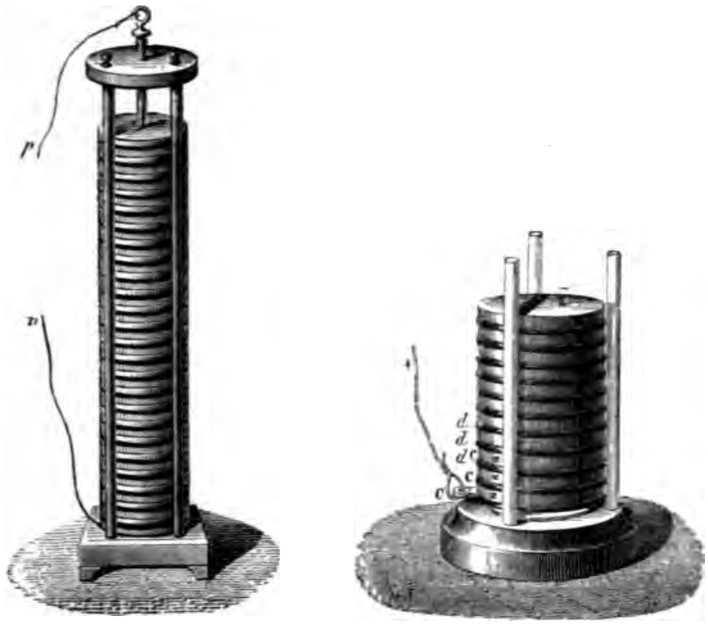

FIG. 399.—Voltaic or column pile.

zinc of the upper extremity, are useless, and are hence omitted. After the omission, the electrical tensions remain distributed as before,—that is to say, the tension is negative on the lower zinc and positive on the upper copper; whence the names *negative pole* and *positive pole* which have been given to the two extremities of the pile.

If the two poles of the pile, thus constructed and charged, are put into communication by means of a conducting body, the two contrary electricities combine, and at the moment of contact a discharge takes place. For instance, on touching the positive pole with one hand, and the negative pole with the other, a shock is felt similar to that given by the Leyden jar; then if contact is continued, a peculiar sensation of heat and trembling is felt. If the two poles are united by two metallic wires, soldered one to the copper end, and the other to the zinc end, a spark is produced at the moment when the wires touch each other; but after this partial discharge, the pile immediately re-charges itself, and the same phenomena can be reproduced for a length of time. It is this property of furnishing electricity in a continuous manner which characterizes this valuable instrument, and gives rise to the various effects which we shall presently describe.

Since the time of Volta the pile has been modified, and it is now constructed under various forms, the most important of which we shall describe; but as all these instruments are founded on the same principle, viz. that of the production of electricity by chemical action, it is necessary to show by experiment the truth of this principle: this we shall now do.

If we plunge a copper plate into a glass vessel containing nitric acid diluted with water (Fig. 400), and place the plate in communication with the lower plate of the condensing electrometer, whilst the liquid, as well as the upper plate, communicate with the ground, we observe, as soon as the two plates are separated, that the gold leaves diverge, and the apparatus is charged with negative electricity. If the order of the communications is changed, and we connect the acid by means of a metallic wire with the lower plate of the condenser, while the other plate and the sheet of copper communicate with the ground, the apparatus will be charged with positive electricity. If, in place of the copper, a metal is substituted which nitric acid does not attack, platinum for instance, no electricity will be disengaged.

Similar results are obtained, that is to say, a more or less energetic disengagement of electricity results, if we excite chemical action between two bodies. Two solutions, one alkaline and the other acid; or, again, two salts, one acid and the other neutral or alkaline, brought into contact, produce electricity, which is positive on the body playing the part of acid, and negative on that which plays the part of base.

Such is the principle of the theory actually adopted to explain the effects of the voltaic pile; and this accounts for the results obtained by this illustrious physicist, and for the experiments by which he tried to demonstrate that a single contact of two heterogeneous bodies suffices to generate the electro-motive force. When the copper and zinc plates were caused to touch one of the plates of the condensing electrometer, he did not observe that the cause of the disengagement of electricity was the chemical action which exerted itself between the oxidizable zinc and the moist hand. The electrical development, which the divergence of the gold leaves afterwards proves, must be attributed to the oxidation of the metal, not to its contact with the copper which plays the part of a simple conductor. Therefore the real voltaic couple is not, as we have already said, the association of the two zinc and copper discs, but rather the zinc, an attackable metal, and the layer of acid with which the cloth disc is soaked. The copper is simply a conductor, on which the developed positive electricity in the acid accumulates, whilst the zinc collects the negative electricity. Volta perfectly proved, and this fact is independent of his hypothesis, that the tension of each kind of electricity in the pile-column increases as the two poles are approached. When these poles are put in communication by two metallic wires, that is to say, conductors, the phenomena of tension disappear, and the pile is discharged; but in proportion as the recombination of the two electricities takes place, the productive cause, which is the chemical action of the sulphuric acid on the zinc, continues to act, and the pile thus becomes a constant source of electricity, so that it is possible to assimilate this

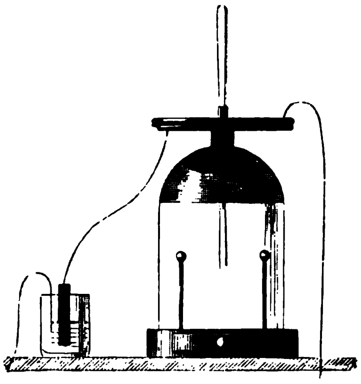

FIG. 400.—Electricity developed by chemical action.

action to an incessant flowing of the two kinds of electricity, negative electricity towards the positive pole, and positive electricity towards the negative pole, through the interpolar wire. These two currents evidently pass in contrary directions through the couples themselves.

It is usual to give a direction to this double current, considering only the movement of the positive electricity. This is called the *current of the pile*, the direction being, as we have just seen—and it is important to remember this—from the negative to the positive pole in the interior of the pile, and from the positive to the negative pole in the portion of the circuit formed by the connecting wires, which are sometimes called *reophores*, or carriers of the current.

We will now speak of the difference in the phenomena of electricity, as we have studied them in the electrical machine and Leyden jar, and those shown by the voltaic pile. In the first apparatus, the electricity developed remains at rest on the surface of the conductors, which has gained for it the name of *static electricity*. On the other hand, the electricity which is constantly produced in a pile and passes through the conductors, is electricity in motion, whence the name *dynamic electricity*. Nevertheless, if we analyse more closely these two classes of phenomena, it is evidently preferable to characterize them in a different manner. When we unite by the help of a conductor the contrary electricities which have accumulated on the two coatings, interior and exterior, of a Leyden jar, there is also, as in the pile, an electric current; but this current lasts but a moment, because the cause which developed the electricity no longer exists. In the pile, the renewing of the electricity takes place in proportion to the recomposition, and the current is continuous. Moreover, the phenomena produced under these two conditions have a very great analogy, and the differences which they present result mainly because, in the first case, the electricities which combine with each other are at very high tension, while, in the second case, they gain in continuousness what they lose in intensity. It is now considered preferable to substitute for the names which we have just mentioned, those of *electricity of high tension*, which is that of the ordinary electrical machine, and *electricity of low tension*, which is the electricity of the pile.

Volta's pile has received various forms, devised with a view of rendering it more convenient, and more especially to increase its energy. In the original column pile, the energy is diminished by the escape of the liquid which the weight of the superposed elements causes to ooze to the outside; this produces secondary outer currents at the expense of the principal current. In the various forms of battery we are about to describe, the principle is precisely the same as that of the voltaic pile.

The trough pile invented by Cruikshank is formed of plates of zinc and copper soldered together, and arranged parallel to each other in a wooden box or trough. The elements, insulated by mastic or resin, are separated into compartments, which are filled with acidulated water when the pile is about to be used. By this arrangement secondary currents are no longer produced.

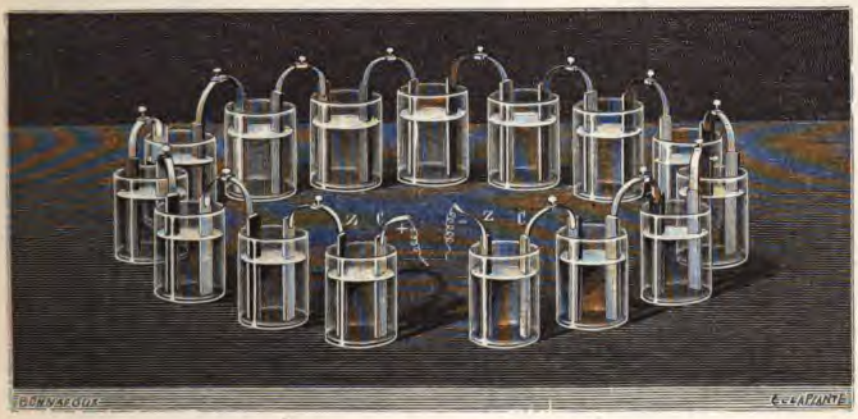

FIG. 401.—Crown or cup pile.

Imagine a series of cups or glasses filled with acidulated water, and arched plates formed, in one case of copper, and in the other of zinc, the extremities of which are inserted in the liquid of two consecutive glasses, so that, in each of these, there are two plates, one of copper, and the other of zinc. On uniting by two metallic wires or reophores the copper and zinc plates of the extreme vessels, we have the *cup pile* invented by Volta, which is also called the *crown pile*, because the elements are generally arranged in a circle, as shown in Fig. 401. Wollaston devised the following arrangement:—A rectangular sheet of copper is curved in such a manner as to envelope within it a zinc plate, from which it is separated above and below by pieces of wood. A band of copper is soldered to the upper part of the zinc, and bent on both sides at right angles, so as to connect the copper plate of the next element; lastly, all these bands are fixed to a cross-piece of wood, which can be raised or lowered at will, together with all the elements. Vessels filled with acidulated water are placed under each element; by lowering the cross-piece the pile can be worked (Fig. 402). The advantage of Wollaston's pile, besides the facility for working it, is the great extent of zinc surface in contact with the acid.

We may mention also the piles of Muncke, and of Oersted, and the spiral pile which was invented by Hare; the latter has great surface with small bulk. It is formed of two long wide bands of copper and zinc, which are both wound round a wooden cylinder; but the two consecutive spirals of the two metals are insulated by rods of wood or pieces of cloth. The whole is immersed in a pail full of acidulated water, when the pile is about to be used.

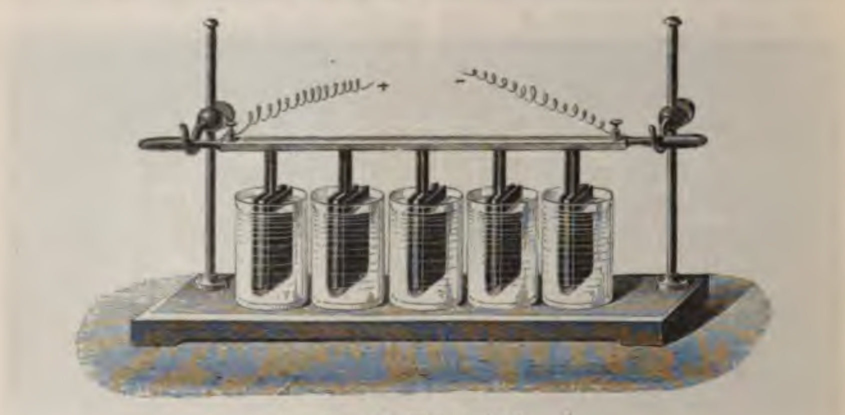

Fig. 402.—Wollaston's pile.

In the piles just described the electrical current is variable; at the commencement of the action its intensity is as great as possible; but different causes tend to progressively diminish the energy. Under the influence of the current, water partially decomposes; the hydrogen, one of the gases which compose it, is disengaged on the zinc as well as on the copper, and forms on the suface of the metal a gaseous stratum, which diminishes the chemical action. Partial currents are also formed which interfere more or less with the electricity disengaged, and thus weaken the interpolar current. Lastly, as by the very fact of the chemical reactions there is combination of oxide of zinc with sulphuric acid, producing a salt, sulphate of zinc, it is evident that the liquid is more and more impoverished as regards acid. Endeavours have been made to render the currents of the piles constant, by modifying the construction of the electro-motive couples. Hence the constant current piles, which are distinguished from variable current piles principally by the placing of each element of the couple in contact with a particular liquid, to prevent the formation of heterogeneous deposits on each of them.

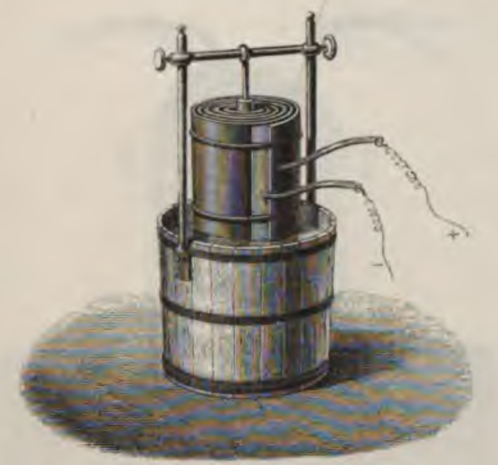

FIG. 403.—Spiral pile.

The batteries most employed are those of Daniell, Bunsen, and Grove. The electro-motive couple of Daniell's pile is represented in Fig. 404. It consists of two vessels, the outer one of glass or earthenware, and the other, placed within the first, of porous earth. Between the two vessels, water acidulated with sulphuric acid is poured, and in the porous vessel a solution of sulphate of copper.

In the first liquid a wide plate of amalgamated zinc, of cylindrical form, is immersed, and in the other a copper cylinder. The following is the manner in which the disengagement of the two electricities takes place on the copper and zinc.

Water is decomposed; its oxygen attacks the zinc and forms oxide of zinc, which combines with the sulphuric acid of the liquid of the outer vessel; the zinc acquires a negative electric tension. The hydrogen of the water, passing through the porous vessel, attacks the sulphate of copper, the oxide of which is decomposed; and the copper is precipitated in the metallic state on the cylinder of the same metal, which acquires a positive electric tension. Each reaction engenders a current, the first from the zinc to the acid, the second from the copper to the solution which surrounds it. The electro-motive force of Daniell's couple is the resultant of these two contrary forces. The final current is not of great strength, but it remains sensibly constant if the precaution has been taken to place crystals of sulphate of copper in the porous vessel. The zinc and copper keep their surfaces intact without any deposit of foreign matters.

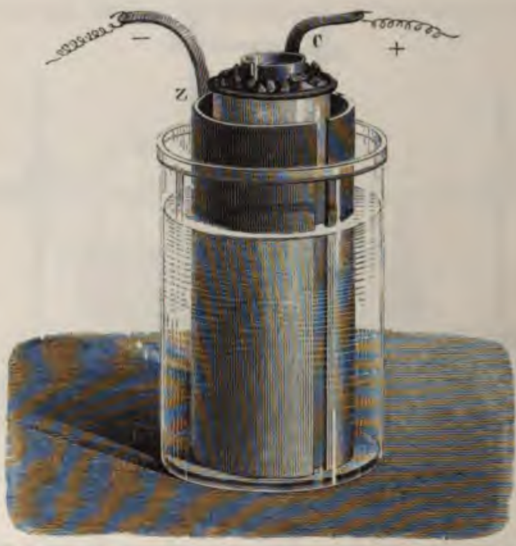

Fig. 404.—Couple of Daniell's battery

Bunsen's couple is arranged like that of Daniell's, but the copper cylinder is replaced by one of gas retort carbon, and the solution of sulphate of copper by nitric acid. Bunsen's couple is preferable to Daniell's on account of the strength of the current, but it is inferior in being less constant.

Grove's battery is constructed as follows:—A vessel composed of any material not attacked by sulphuric acid is partially filled with that acid diluted in the proportion of one acid to eight water. In this vessel is inserted a zinc plate which is curved in the form of an U. Into this U is inserted a porous vessel containing nitric acid and a plate of platinum. The platinum of one cell is connected with the zinc of another, and so on. This battery is one of very great power.

By uniting several similar couples by their contrary poles, Daniell's, Bunsen's, and Grove's batteries are formed, the strength being proportional to the number of elements thus united. The negative pole in both piles is the zinc of the last element; and the positive pole the last copper in Daniell's pile, or the last platinum plate in Grove's, or the last carbon in Bunsen's pile, as shown in Fig. 406.

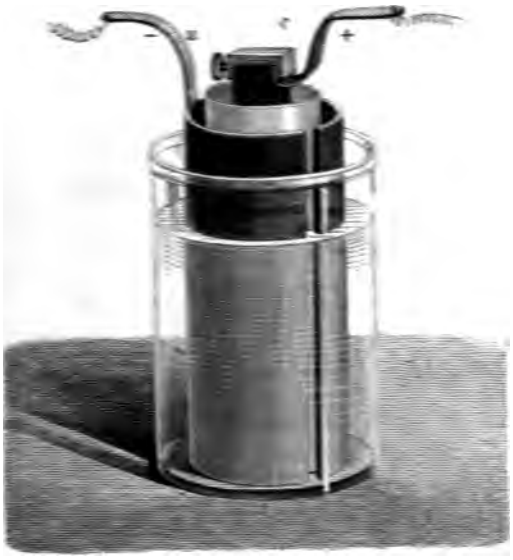

FIG. 405.—Couple of Bunsen's battery.

We may now describe some of the more remarkable phenomena which give rise to the production of electricity of low tension; that is to say, of electricity produced by voltaic piles under the influence of chemical action. Heat, light, chemical combinations and decompositions, nervous shocks and various physiological effects, are among the various order of phenomena which are manifested by the wonderful apparatus with which Volta, sixty-eight years ago, enriched science.

The calorific effects of piles are much more intense than those obtained by the discharge of electrical apparatus at high tension, as the following experiments will show: if the circuit of a few couples of Wollaston's battery is closed, by connecting the reophores with a metallic wire of small diameter and a few centimetres in length, the wire becomes heated under the influence of the current which passes through it, soon it acquires a red heat, then melts, and is volatilized. With a pile of 21 of Wollaston's elements, platinum wires of 5 millimetres in diameter and 7 centimetres in length can be melted. The constant current piles are more powerful still; with 50 of Bunsen's elements iron or steel wires, more than 30 centimetres in length and of the size of a knitting needle, fuse and burn, sending out brilliant sparks in all directions. The size of the elements has more influence on the intensity of the heat effects than the number of couples used. Davy fused various metals, and observed the curious phenomena of coloration which proceed from the combination of metals with oxygen by the use of a battery possessing large surface. Iron burns with a red light; zinc gives a flame of a bluish white; gold, yellow; silver, white, with a greenish tint on the edges; copper, green; tin, purple; lead, yellow; platinum alone melts without being oxidized, and falls in drops of dazzling brightness.

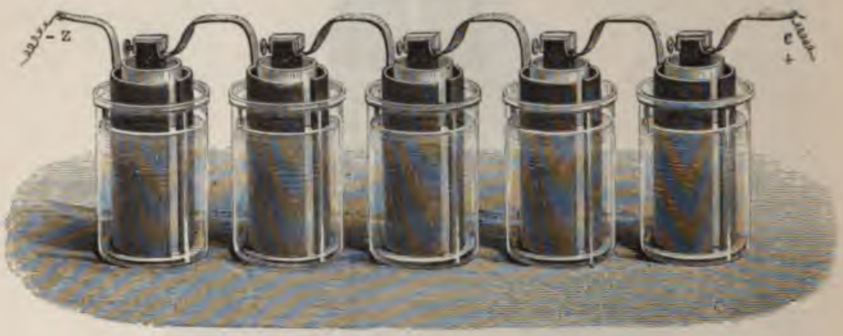

FIG. 406.—Pile formed by five Bunsen's elements.

We have seen that different metals do not conduct electricity equally well: those which offer to the current the greatest resistance become heated to the greatest extent. If we take two wires of equal diameter, formed of different metals, one of which becomes incandescent, while the other remains dark, the latter is always formed of the best conducting metal. This fact has been proved by forming a metallic chain of links which are alternately silver and platinum, and by attaching the two extremities of the chain to the reophores of a pile; when the current passes, the platinum begins to redden, becomes incandescent, and even melts, whilst the silver remains unchanged. The conductibility of this last metal for electricity is 100, whilst that of platinum is only 8. It is for this same reason, that is to say, on account of the different resistance offered to the passage of the same current, that two wires of the same metal and unequal diameter heat unequally; as the larger offers less resistance, it consequently heats less than the smaller. When a metallic wire, raised to a red-heat by the voltaic current, is plunged into water, the incandescence ceases, which is but natural, since it transfers part of its heat to the liquid, but a curious experiment of Davy's proves that this phenomenon has also another cause. Having made a metallic wire red-hot by means of the voltaic pile, he cooled a portion of the wire by touching it with a piece of ice; immediately the part not touched was raised to a white heat and melted, which fact receives the following explanation:—The cooling diminishes the resistance of the wire, and thus increases the intensity of the current, which then becomes strong enough to melt the portion of the wire which the first intensity had only raised to redness. In the case of the wire immersed entirely in water, the incandescence of which ceases, the phenomenon is complete; there is the cooling by contact with the water, diminution of the resistance of the wire and increase of the intensity of the current; and these two last causes produce contrary effects.

Voltaic batteries produce electricity at low tension; it is therefore not astonishing that the reunion of the reophores of a charged pile does not produce a spark, or, at least, only a small one. But if a very powerful pile is used, composed of a great number of elements, and if instead of closing the circuit by placing the wires in contact a small space is left between their extremities, sparks will appear close upon each other, which form a continuous light if the two wires are terminated by charcoal points. This continuous light is known as the voltaic arc. Davy, with a pile of 2,000 couples, each having 4 square decimetres of surface, obtained a dazzling light, which appeared in a continuous manner in the space between two charcoal points. The space was at first only half a millimetre; but the light once produced he could separate the coal points to a distance of 11 millimetres. He then saw a phenomenon of great beauty. The electric light spread itself between the two electrodes in the form of an arch, the convexity being above, and of such intense brightness that the eye could scarcely endure it. *In vacuo* the length of the arc is greater than in air. Since the time of Davy, the production of the voltaic arc has been rendered more easy, and, thanks to the induction apparatus which we shall describe in a succeeding chapter, it has also been employed for lighthouses. The arc develops a heat of extreme intensity; metals melt in it like wax in the flame of a lamp.

The most refractory bodies have been melted and volatilized by M. Despretz, at first with a pile of 600 couples, then by using an induction apparatus. Oxides of zinc and iron, lime, magnesium and aluminium were reduced to globules; graphite, volatilized, deposited a dust on the electrodes which, when examined with the microscope, appeared as very small octahedral crystals: with this powder, rubies have been polished; it has therefore been concluded that the graphite —which, like the diamond, is of pure carbon—had been crystallized under the influence of the intense heat of the arc, and changed into very small diamonds.

The chemical effects of the pile present the greatest interest. Decomposition of water is one of the most important. To effect this the apparatus represented in Fig. 407, called a Voltameter, because the quantities of water decomposed in a given time by the voltaic current serve to measure the intensities of these currents, is employed. It consists of a glass vessel, the bottom of which is covered with mastic and pierced by two platinum wires which unite at the extremities of the reophores of the pile; the vessel is filled with water, with the addition of a few drops of sulphuric acid, which renders the liquid a better conductor. Two graduated glass tubes cover the platinum plates. When the current passes, bubbles of gas are seen to be disengaged round the plates and to rise to the top of each tube. One of these gases is hydrogen, the other oxygen, and the volume of the first is always double that of the second. Moreover the disengagement of the oxygen always takes place from the plate which is attached to the reophore of the positive pole, whilst the hydrogen is disengaged at the negative pole.

By the aid of the pile, Davy succeeded in decomposing the oxides of the alkaline metals, potash for example, from which resulted a new metal, potassium. A great many other chemical compounds, acids and bases, have been resolved into their elements by the influence of the voltaic current, and chemistry possesses in it a new and powerful means of analysis. We may mention as another example of decomposition, that of a metallic salt; we shall see presently the importance of the applications which the arts have made of this mode of electrical motion.

The salt known in chemistry as sulphate of copper, is a compound of two binary combinations; on the one hand, sulphuric acid, and on the other, protoxide of copper. Sulphur and oxygen form sulphuric acid; copper combined with the same gas, oxygen, forms the metallic oxide. Let us examine how the separation of these elements can be made under the influence of electricity disengaged from the reophores of a pile.

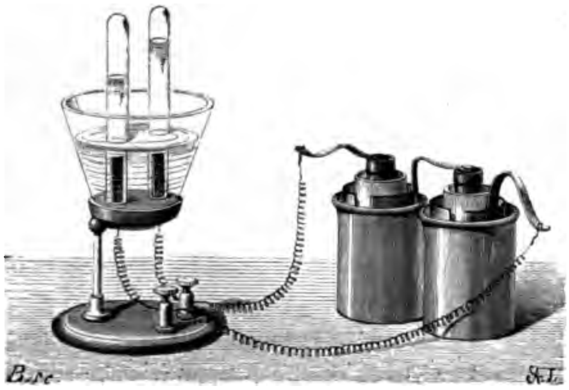

FIG. 407.—Decomposition of water by the voltaic pile.

In a vessel which holds a solution of sulphate of copper, two platinum plates attached to the reophores of the pile are immersed. Under the influence of the electric current, bubbles of oxygen are seen to be disengaged around the plate which corresponds to the positive pole—this is called the *positive electrode*—and the copper is deposited in a metallic state on the surface of the plate which forms the negative electrode. Thus the salt has been decomposed; its base, separated from the acid, is itself decomposed into oxygen and copper: as the sulphuric acid became free, it was carried towards the positive electrode. We may satisfy ourselves of this by testing with litmus paper different parts of the solution, and we shall see that the red tint of the test paper is strongest in the vicinity of the positive electrode. The phenomena of chemical decomposition by voltaic electricity are extremely numerous and complex; in fact, they would require a volume to describe them. We will confine ourselves to the indication of a singular fact which always accompanies electrolytic action (this is an expression deduced from the word Electrolysis, by which Faraday distinguished decomposition by the pile). When the electrodes have been in use some time, if they are taken out of the saline solution, plunged into pure water, and put in communication with the wires of a galvanometer, it will be remarked with this instrument, which will be described shortly, that a current passes in a contrary direction to the original current; that is to say, from the negative to the positive electrode. It is then said that the electrodes are *polarized*. The secondary current of which we speak is only temporary, and is due to the accumulation on the electrodes of the deposit produced by electrolysis; it ceases as soon as these deposits are destroyed by the effect of the fresh chemical actions engendered under its influence.

Commotions or nervous shocks, caused by the passage of a current from a pile through the organs of men or animals, are greater as the pile is formed of a larger number of couples. The effect produced depends only on the tension of the pile, a tension which increases with the number of the elements, the surface being unable to effect a like result. It is dangerous to be exposed to the shock of a powerful pile. Gay-Lussac felt for more than a day the violent shock he received by touching the two reophores of a trough pile of 600 couples. The sensation is perceived with the greatest strength at the moment when the circuit is closed. Then the arms and chest are shaken, but afterwards only a sort of trembling is felt in the muscles of the arms and hands; when the communication is at last broken, a fresh shock is felt, more feeble than the first. Moreover it is necessary to distinguish two sorts of physiological effects of the pile; the simple muscular contraction, without pain, and a sharp and painful sensation, without contraction. It is now known that the nerves are divided into sensible nerves and motor nerves: the first have the function of transmitting the sensations to the nervous centres, the brain and the spinal cord; while the motor nerves execute, so to speak, the orders which come from the brain itself, and give motion to the muscles. These two kinds of nerves, the one motor and the other sensory, are inserted by two kinds of root, and are united for a certain space; they are then separated and divided into two branches, one carrying sensibility to the organs, the other giving them movement. Now, if the circuit is closed after having placed one of the reophores on the common fibres of the two orders of nerves, there is both contraction and painful sensation in the animal subjected to the experiment. But there is only contraction if the ramifications of the motor nerves are touched, and only pain if the ramifications of the sensory nerves are first touched by the wire.

The physiological effects of the pile have been the object of numerous and very interesting experiments, both on living and dead animals. Galvani and his kinsman, Aldini, professor at Bologna, had the honour of commencing this fruitful study of the influence of electricity on animals. They showed that the passage of the current produces in the muscles of dead animals contractions frightfully like the movements which they have during life. Aldini's experiments on the bodies of two criminals beheaded at Bologna, in 1802, are particularly celebrated; those also of Dr. Andrew Ure on the body of a criminal an hour after he was taken from the gibbet. One of the nerves of the eyebrow was put into connection with one of the wires of the pile; the heel with another pole: when the face of the criminal contracted in such a hideous manner that one of the assistants fainted. No expression can describe the horror of the observers in the terrible scene which followed from this experiment.

The action of the pile on living beings is not less curious; and its effects interest us more, since we have discovered their good influence in the curing of certain illnesses, principally nervous affections. The action of the voltaic current on the organs of the senses produces precisely the sensations belonging to each of them. By exciting the optic nerves, the sensation of light is produced, and that of sound, if the nerves of the ear are touched.

CHAPTER V.

ELECTRO-MAGNETISM.

Action of a current on the magnetic needle; Oersted and Ampère—Schweigger's multiplier; construction and use of the galvanometer—Action of magnets on currents—Action of currents on currents—Influence of the terrestrial magnetic force—Ampère's discoveries; solenoids; the electrical helix; theory of magnets—Magnetism of soft iron or steel discovered by Arago; magnetization by means of helices—The electro-magnet; its magnetic power; its effects.

TWENTY years after the discovery of the voltaic pile, a new fact of great importance was brought to light by Oersted, a Swedish physicist, professor in the University of Copenhagen: he discovered that the electric current acts on the magnetic needle. For some time the existence of a relation between magnetic and electrical phenomena had been suspected: the perturbations undergone by the compass on board vessels struck by lightning had been noticed; as also on those whose masts had presented the electrical phenomenon known as the fire of Saint Elmo; it was known that the discharges of electric batteries agitated a magnetic needle placed in their vicinity. But these facts afforded but vague ideas as to the actual correlation which exists. In 1820, the year in which Oersted made his discovery, Ampère studied and propounded the laws of this action, and showed, moreover, that the currents themselves act on other currents.

Lastly, Arago discovered the magnetism of soft iron and that of steel under the influence of the current of the voltaic pile. These experiments were the starting points of a multitude of new ones, which in a short time changed the aspect of this branch of science, by demonstrating that magnetism and electricity are varied manifestations of the same cause. We shall see hereafter, that the discoveries which revealed the real nature of magnetism, and gave so much advance to theory, have not been less fruitful in ingenious and useful applications.

Let us now return to Oersted's experiment. Imagine a magnetic needle suspended on a pivot, and moveable in a horizontal plane; we know that it will then place itself in the magnetic meridian, making a constant angle with the north and south geographical meridian line. If we then place parallel to the needle, and at a short distance above, a metallic wire whose extremities are joined to the reophores of the pile, we notice that so soon as the current passes, the needle is deviated from its position; it leaves the magnetic meridian and sets itself across the current. If, instead of placing the wire above the magnetic needle, it is placed at the same distance below it, the needle is again deviated and sets itself across the current. In repeating the same two experiments and changing the direction of the voltaic current,—that is, if it first passes from south to north, it is now caused to pass from north to south,—we observe that the needle is again deviated and sets itself at right angles to the current, but in precisely opposite directions to those which it assumed under the influence of the direct current.

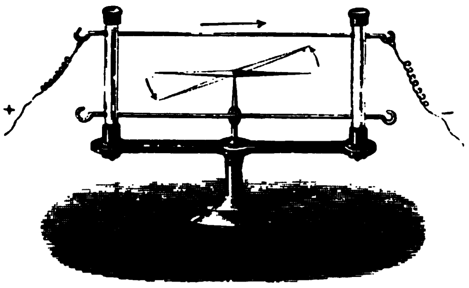

FIG. 408.—Action of an electrical current on the magnetic needle.

Again, if, instead of placing the wire parallel to the needle, it is placed perpendicularly to the horizontal plane opposite one or the other pole, the needle will be seen to undergo again the same deviations, corresponding to the four fresh dispositions which can be given to the voltaic current,—from top to bottom, bottom to top, and opposite either to the southern or northern pole of the needle.

Such are Oersted's experiments, and Ampère succeeded in formulating, in a single statement, the law which governs them.

He conceived the ingenious idea of personifying the current, by figuring it as a person laid along the current, whose face, in all possible positions, is always turned towards the centre of the needle. The current, which passes from the positive pole of the pile to the negative pole through the wire, is supposed to enter by the feet of the person and to come out at his head; then the current is found to have a right and a left, which are those of the person himself: therefore, the following is the simple statement by which Ampère has connected the various conditions which furnish Oersted's experiment:—

When an electric current acts on a magnetic needle, the southern pole of the needle—which is always that which is directed towards the north—*is deviated towards the left of the current.*

Thus, if the current passes parallel to the needle, and from south to north, the case is met by that of the two figures, 409 and 410. In the case of the upper current, the south pole A is deviated to A′ to the left of the current,—that is, towards the west; if the current passes below the needle, it is always to A′—to the left of the current that the south pole A is deviated, but now this pole moves towards the east. If the direction of the current is changed, still remaining parallel to the needle,—that is to say, if it passes from north to south,—the southern pole will be deviated towards the east, in the case of the upper current, and to the west, in the case of the current placed below the needle. Lastly, when the current is vertical, it can be either ascending or descending, and placed either opposite the northern or southern pole of the magnet. In the case represented in Fig. 411 the southern pole is seen to deviate to the east; that is, to the left of the

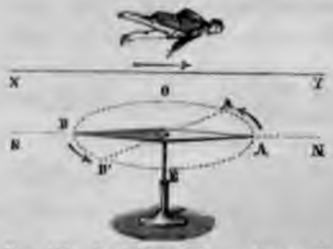

FIG. 409.—Deviation of the southern pole towards the left, under the influence of the upper current.

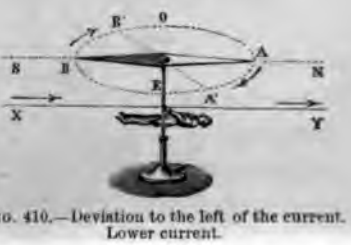

FIG. 410.—Deviation to the left of the current. Lower current.

current. We will leave the reader to find the direction of the needle in the other cases; a task which has been rendered easy by Ampère's law.

The laws which regulate these observations were studied by Biot and Savart and by Laplace. Bearing in mind the fact that the influence of the current depends on its intensity and, consequently, on the surface of the couples of the pile employed, it diminishes in proportion as the distance from the needle increases. It must not be forgotten that in the presence of a voltaic current, the needle is subjected to two influences at the same time, viz. that of the current itself, and that of the earth, which acts on the needle like a magnet; the deviations observed are, therefore, an effect resulting from these two simultaneous actions. If, by any means, we can render the direction of a magnetic needle independent of the action of the earth—it is then called an *astatic needle*—the current deviates the needle to a right angle, whatever may be its intensity. The deviation then indicates only the presence of the current, without proving its energy.

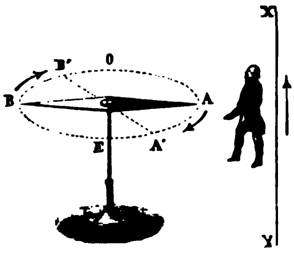

FIG. 411.—Deviation to the left of the current. Vertical current.

Let us now see how we can utilize the action of electrical currents on the magnetic needle, in the construction of apparatus which serve both to prove the presence of small currents, and to measure their intensity. We will first describe the apparatus called *Schweigger's multiplier*, from its inventor:—

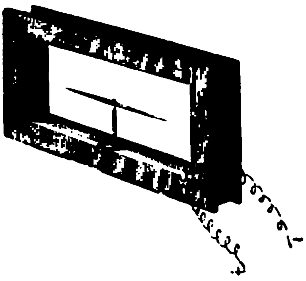

FIG. 412.—Schweigger's multiplier.

It consists of a wooden frame (Fig. 412) round which a copper wire is wound a great number of times; this metallic wire is entirely covered with an insulating substance, gutta-percha, silk, cotton, &c., so that an electric current entering by one of the extremities of the wire, and issuing from the other, cannot pass from one spiral to another without having traversed the whole length: in a word, it is obliged to pass through all the successive windings. If the frame is placed vertically on one of its sides, in the plane of the magnetic meridian, and if a magnetic needle is placed in the inside, suspended freely on a vertical pivot, a good instrument will be obtained for showing, by the deviation of the needle, the existence of an electrical current, however slight it may be. To effect this, it is sufficient to attach the extremities of the wire of the multiplier to the two reophores of the pile or of any voltaic circuit; so soon as the circuit is closed, the presence of the current will manifest itself by a greater or less deviation of the needle.

We will now analyse this effect, and examine how the action of the current is multiplied by the arrangement we have just described, and, for this purpose, we may first consider one of the circuits of the wire wound round the frame; the current passes from M to N, then to Q and P, and at R leaves the needle. Now, if we compare it with Ampère's statement, we shall see that each of the four portions of the current tends to deviate the southern pole from a to a', consequently towards the east, or, in other words, to the front of the figure; each of them acts like an insulated current, or better, like an indefinite portion of the current near the needle. The total deviation will be then stronger than if the current only followed one of the sides of the rectangle. Now, at the following winding, the current acts again in the same manner, and it is the same for all the successive windings, so that its influence on the magnetic needle is multiplied by the number of the windings of the wire. Hence the name of *multiplier* is given to the instrument.

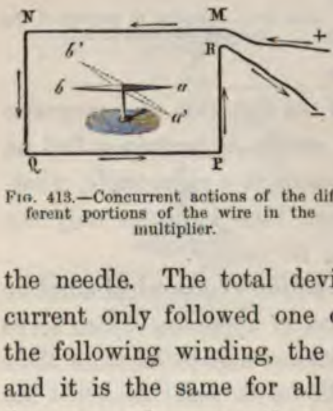

FIG. 413.—Concurrent actions of the different portions of the wire in the multiplier.

The magnetic needle is in this experiment, as we have already stated, submitted to two forces: the directive action of the earth, in virtue of which it places itself in the magnetic meridian; and the action of the current, which tends to cause it to assume a position at right angles to the first. The deviation of the needle is produced by the resultant of these two actions. To increase the deviation, and to give a greater sensibility to the multiplier, Nobili conceived the idea of substituting for the magnetic needle a system of two parallel magnetic needles, fixed on the same axis, with their poles of the same name placed in contrary directions. The suspension being by a silk thread without torsion, if the needles have the same magnetic force, their system will be *astatic;* that is to say, will remain in equilibrium, whatever may be its angle with the meridian. A system exactly astatic would not fulfil the end which is proposed, which is to measure the intensity of the currents by the deviation, as then the deviation would always attain the maximum of 90°, whatever the power of the current. But if one of the needles, the lower one for example, is a little more magnetized than the upper one, the system will continue to be influenced by the earth; but this action will be very feeble, and therefore the action of the currents through the intervention of the multiplier will be, on the contrary, considerable. The introduction of the compensated needles in Schweigger's multiplier led Nobili to the construction of the *galvanometer* (Fig. 415), the most delicate

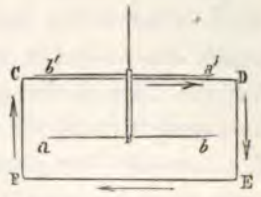

FIG. 414.—System of two astatic needles.

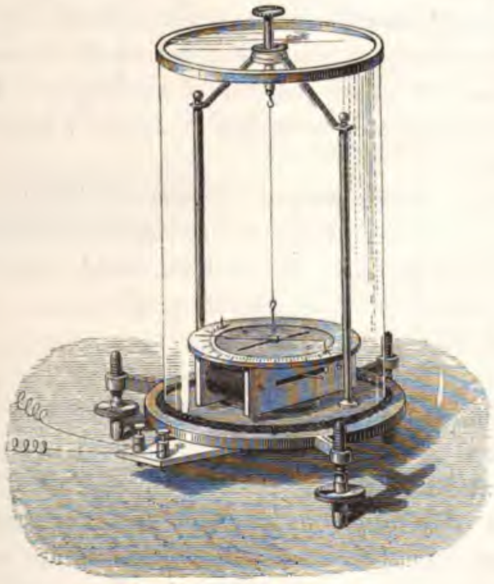

FIG. 415.—Galvanometer.

apparatus for determining the existence, strength, and direction of weak electrical currents. The following is the manner in which this instrument is used:—

The ivory frame around which the insulated wire is wound, and which is below the dial, can be moved in a horizontal plane by an outside screw; and it is first brought into a plane of such a nature that the zero of the graduation of the dial corresponds to one of the extremities of the needle. It is now certain that the rounds of copper wire are parallel to the two needles of the system. The apparatus is furnished with levelling screws, so that it can be placed horizontally; and a glass shade protects the suspending thread and the needles themselves against the agitation of the exterior air. The frame includes a rectangular ivory plate, which has two brass buttons, at each of which terminates the extremity of the two wires of the multiplier. To these buttons, or binding screws, the reophores of the current, the direction and intensity of which are to be determined, are attached: as soon as the circuit is closed, and the current passes along the rounds of wire, the upper needle is seen to deviate to the right or left of its position of equilibrium; the direction of this deviation indicates, according to Ampère's law, the direction of the current.

The intensity of the current is measured by the arc which either of the extremities of the needle has traversed, starting from the zero of the graduation. It has been found that, if the deviation does not exceed 20°, it is sensibly proportional to the intensity of the current.

We have just seen the action of voltaic currents on the magnetic needle, and how this influence has been utilized in constructing an apparatus of extreme delicacy, to show the direction and intensity of a certain current. We may now state that magnets exercise on currents an action equal to that to which they themselves are submitted, but in a contrary direction. Thus, when a strongly magnetized magnetic bar A B (Fig. 416) is placed in a horizontal position below or above a metallic wire forming a voltaic circuit, and free to turn round the points of suspension, the wire is seen to set itself across the magnet, in such a manner that the south pole of the bar is always to the left of the current which is nearest to it. When the direction of the current is changed by the reversal of the reophores which terminate the two extremities of the wire, the wire immediately makes a rotation of 180° on itself; the southern pole of this latter is still to the left of the current, according to Ampère's law.

We have now arrived at Ampère's beautiful discovery, which immediately followed that of Oersted's, as to the action of voltaic currents on each other. We will confine ourselves to the statement of the principal laws which govern the reciprocal influence of currents, laws whose experimental verification is easy, in the numerous particular cases which they comprehend. Ampère has demonstrated that:—

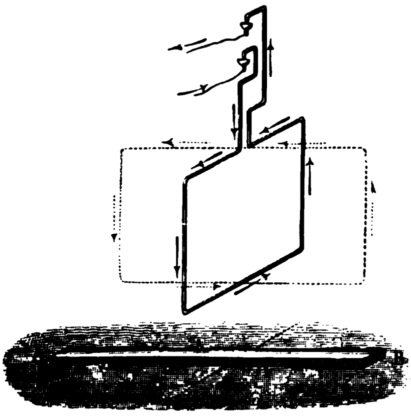

FIG. 416.—Action of a magnet on a current.

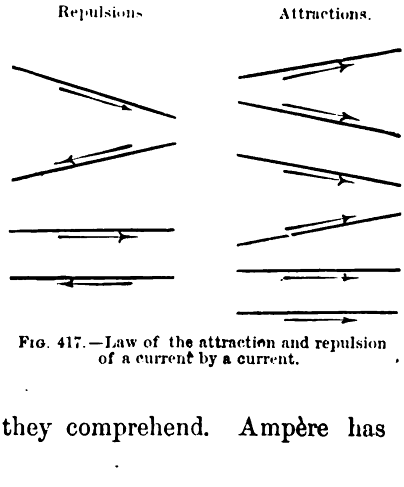

FIG. 417.—Law of the attraction and repulsion of a current by a current.

1st. *Two parallel currents, which pass in the same direction, attract each other: while they repel each other if they pass in a contrary direction.*

2nd. *Two non-parallel currents attract each other, if at the same time both approach or recede from the apex of the angle formed by the ends produced; they repel each other, if one of the currents approaches the apex of the angle, whilst the other recedes from it.*

Fig. 417 represents the three cases of attraction and two cases of repulsion to which these laws refer. Thus then, on the one hand, electrical currents act on magnets, and magnets act on currents: while, on the other hand, currents act on each other. Hence, there is only a step to assimilate magnets with currents; Ampère has indicated this, and has brought to the help of theory the control of experiment. He discovered that the earth itself acts on the currents; that if a rectangular instrument similar to that of Fig. 416 is left to itself, and an electrical current passed through it, the apparatus turns round on its vertical axis and places itself spontaneously across the magnetic meridian; the ascending portion of the current is carried to the west and the descending portion to the east. M. Pouillet, by some clever arrangements, has shown that an insulated vertical current, moveable round an axis which is parallel to it, is transported of itself to the magnetic west or east, according as it is ascending or descending, whilst the action of the earth on the horizontal branches of Ampère's apparatus is *nil*. To determine the nature of these facts Ampère constructed a static apparatus,—that is to say, a magnetic system indifferent to the action of the terrestrial globe; then causing a fixed current to act on it, placed horizontally in a direction perpendicular to the magnetic meridian, from east to west, he saw that the action of this current was precisely the same as the action of the earth. He concluded that the magnetic action of the earth on the magnetic needle is due to electrical currents which continually circulate perpendicularly to the magnetic meridian, their direction being from east to west. These various currents, whatever may be their number, may be considered as composing a single current; and experiment shows that, in our latitudes, its position is situated towards the south.

Pursuing these beautiful generalizations, Ampère showed that a magnet may be assimilated to an assemblage of circular vertical and parallel currents passing in the same direction. An assemblage of such currents indeed—experiment will show us—when freely suspended so as to be able to turn in a horizontal plane, places itself, when submitted to the action of the earth, in the magnetic meridian; in fact, it behaves exactly like a magnetic needle. Ampère constructed a helix or *electrical magnet* in this way:—He took a metallic wire and rolled it round a cylinder in equidistant coils, giving it the form represented in Fig. 418; he then brought the two extremities of the wires longitudinally above the coils, and curved them in such a way that the whole could freely turn round a vertical axis; next, he attached the two ends of the wire to the reophores of a pile. When the current passes in the direction marked by the arrows, the *solenoïd*—the name given to the apparatus by Ampère—places itself in a position of stable equilibrium; each coil is in a vertical plane, its direction being from magnetic east to west; the axis of the solenoïd coincides then with the magnetic meridian, exactly like a magnetic needle. If the direction of the current is changed, the solenoïd is seen to be displaced; and after having moved through 180°, it places itself in its original position, its longitudinal axis being always in the magnetic meridian, but it is turned about. Lastly, an element of the solenoïd, suspended so that it is able to turn freely round an axis perpendicular to the magnetic meridian, assumes an inclination which is precisely equal to that of the magnetic needle.

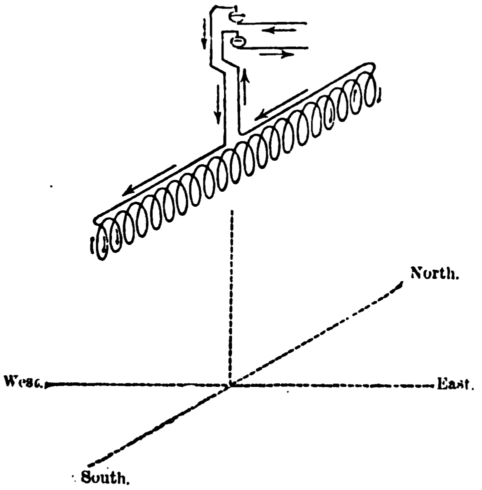

FIG. 418.—Direction of a solenoïd in the meridian, under the action of the earth.

Thus, ordinary magnets, and solenoïds or electrical magnets, conduct themselves in the same manner when under the influence of the magnetic action of the earth. But the analogy has been pushed further; Ampère has shown that the extremities or poles of two solenoïds exercise on each other attractions and repulsions of the same nature as the attractions and repulsions of the poles of magnets: poles of the same name of solenoïds repel each other; while poles of contrary names attract each other. Lastly, the same actions manifest themselves, if the pole of a solenoïd is presented to one or other of the two poles of a magnetic needle. The similarity is complete, and Ampère was able to form his theory of magnetism in all its exactness, a theory which assimilates magnetic phenomena with dynamic electrical phenomena. The following is a brief *résumé* of this beautiful theory:—

The terrestrial globe is continually traversed by numerous electrical currents, induced perhaps by chemical action. These various currents, with directions and intensities probably different and variable, produce on magnets the same effect as a single current, resulting from the composition of the elementary currents, circulating from east to west, in a direction contrary to the earth's movement of rotation. A magnetic substance, iron, steel, &c., also becomes the seat of elementary electrical currents, circulating round certain groups of atoms. In soft iron, and in magnetic bodies which are not endowed with polar magnetism, these currents move in all directions, so that the resulting effect is *nil*. In magnets, on the contrary, the particular currents have all the same direction; for example, they circulate as the arrows indicate in Fig. 419, in which is shown a transverse section of a magnetic bar. In the neighbouring or contiguous portions in *b*, *b′*, *a*, *a′*, &c., the currents are of contrary directions, and are destroyed; so that the total effect is reduced to the exterior effect, which leads us to consider the contour of each edge as being traversed by a single current. The same effect will take place in all the sections, and the magnet will be constituted as indicated in Fig. 420.

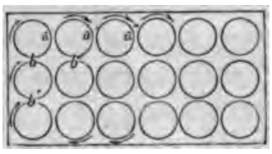

FIG. 419.—Particular currents of magnets.

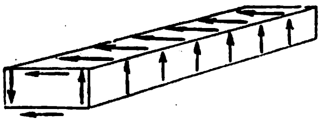

FIG. 420.—Resulting currents at the surface of a magnet.

We therefore see that, according to Ampère's theory, every magnet may be considered an equivalent to a solenoïd.

In regard to magnetic substances, such as soft iron, the vicinity of a magnet causes them to momentarily acquire polar magnetism, by the same action that the currents of solenoïds exercise on the currents of which they themselves are a part. This influence modifies the direction of these elementary currents, and makes their resultant no longer *nil;* thus is produced induced magnetism. We shall find, moreover, that permanent magnetism is perfectly explained by Ampère's theory; but in this case, experiments must instruct us, and will reveal to us phenomena of the greatest interest.

In September 1820, Arago, a short time after Oersted's and Ampère's discoveries, made the following experiments:—He inserted into a mass of iron filings a copper wire which united the two poles of a pile; on drawing out the wire without interrupting the current, he saw its surface covered with particles of iron filings, arranged transversely; as soon as the current was interrupted, the particles detached themselves from the copper and fell. To assure himself that this was temporary magnetism, not the attraction of an electrified body for light bodies, he substituted for the iron filings a non-magnetic substance, and the phenomenon did not take place. On placing needles of soft iron, and then of tempered steel, very near the copper wire, he noticed that the action of the current transformed them into magnetic needles, having their southern pole always to the left of the current; this result agreed with the then recent experiments of Oersted. Soon after, Arago and Ampère noticed that the magnetism of soft iron, or that of steel, was developed with much greater intensity by placing the needle in the interior of an electrical helix. The reophore wire of a pile was coiled round a glass tube; then, having placed in the axis of the latter the needle to be magnetized, they passed the current through the wire: magnetization was immediately produced, but, as might have been expected, it was temporary in soft iron, and permanent in steel.

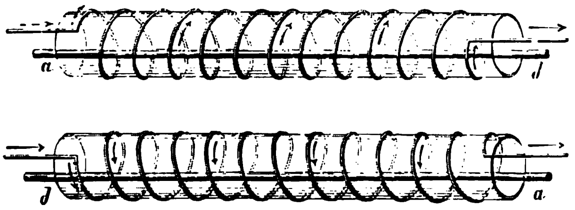

FIG. 421.—Magnetization of a steel needle by a solenoïd: dextrorsal and sinistrorsal spirals.

Glancing at Fig. 421, we see that there are two ways of coiling the wire round the tube. Supposing the tube to be horizontal, the wire can be coiled from right to left, each round being coiled from top to bottom on the side of the tub turned towards the operator; this is the dextrorsal solenoïd: or, again, the wire may be coiled in the same way, but passing from left to right; this is the sinistrorsal solenoïd. If the current traverses the coils of the spiral from left to right, as indicated by the arrows, the magnetization will give a southern pole as to the needle, to the left in the dextrorsal spiral; the southern pole will, on the contrary, be to the right in the needle of the sinistrorsal spiral.

In both cases, the southern pole is always to the left of the current, according to Ampère's law.

By this process of magnetization, so simple and wonderful, secondary poles can be produced at will on bars to be magnetized, which are called, as we have before seen, consequent points. To effect this it is sufficient, after having coiled the wire in one direction round the tube, to coil it in the opposite direction at each of the points when we desire to produce a secondary pole. The whole spiral is thus formed of a dextrorsal spiral, followed by a sinistrorsal spiral, and so on (Fig. 422).

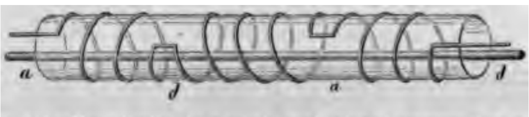

FIG. 422.—Magnetization by a spiral: production of consequent points.

We have mentioned that soft iron, surrounded by a magnetized spiral, assumes temporary magnetism. The magnetic force thus developed is more powerful according as the iron is more homogeneous and pure, and as the number of the coils of the spiral is greater. To realize this last condition, the metallic wire is surrounded by an insulating envelope, as in Schweigger's multiplier for example, by a silk thread: it is then coiled round a piece of soft iron, drawing the coils as close as possible, in order to get a great number of rounds. It then becomes what is called an *electro-magnet;* that is to say, a magnet whose magnetic power subsists during the passage of the current of the pile, and ceases when the current is discontinued. The form of a cylinder, bent like a horse-shoe, is usually given to electro-magnets, each branch of which is covered with a portion of wire (Fig. 423). The spirals here appear coiled in an opposite direction, but the direction of the coiling is in reality the same in both branches, if we suppose the cylinder of soft iron straightened. We have then, at the two extremities, as soon as the current passes, two poles of contrary names. Electro-magnets are also made with two parallel iron cylinders of soft iron, united on one side by an iron plate, and on the other by a copper plate (Fig. 424). The power of an electro-magnet depends not only on the number of coils of the conducting wire of the current, but also on the intensity of the latter, and the dimensions

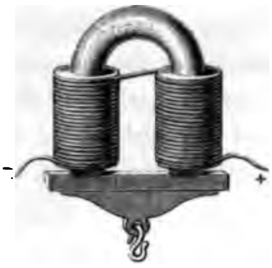

FIG. 423.—Horse-shoe electro-magnet.

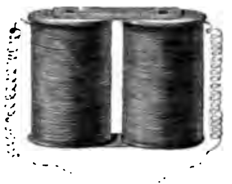

FIG. 424.—Electro-magnet.

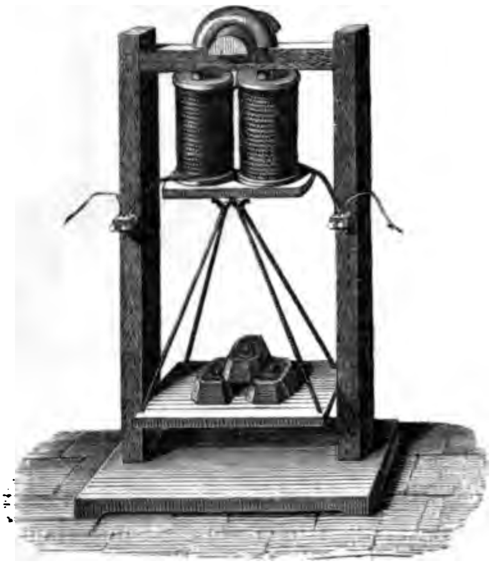

FIG. 425.—Electro-magnet with its charge.

of the soft iron which forms it. The electro-magnet constructed by M. Pouillet for the Faculté des Sciences of Paris, is capable of supporting a weight of several thousand kilogrammes.

Many curious experiments can be made with electro-magnets; we may, for example, form a magnetic chain, by placing a heap of magnetic substances, iron filings, nails, &c. below the poles. As soon as the current passes, the little bodies are attracted by the poles, which magnetize them by induction, and then get mixed together, as seen in Fig. 426. As soon as the circuit is broken, all the fragments of the chain fall simultaneously.

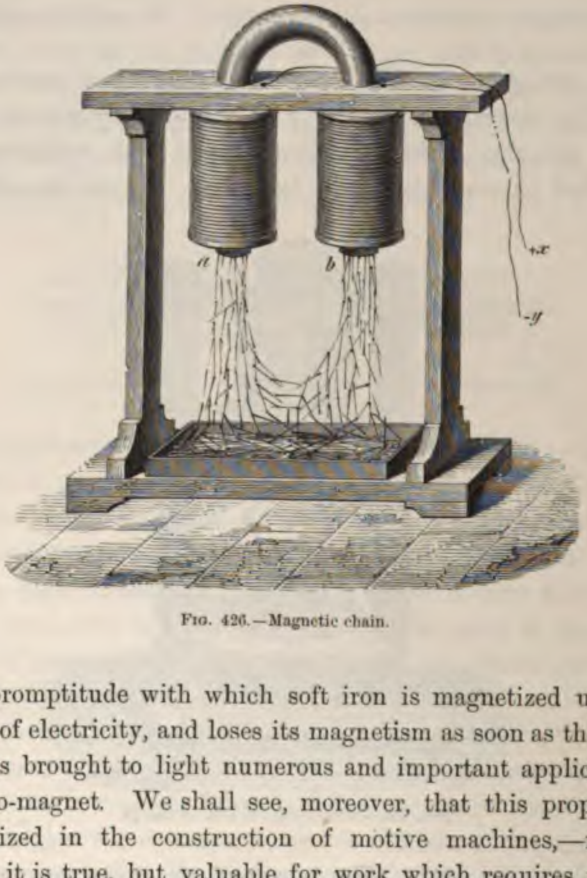

Fig. 426.—Magnetic chain.

The promptitude with which soft iron is magnetized under the influence of electricity, and loses its magnetism as soon as the current ceases, has brought to light numerous and important applications of the electro-magnet. We shall see, moreover, that this property has been utilized in the construction of motive machines,—not very powerful, it is true, but valuable for work which requires precision and regularity. In the electric telegraph especially, the electro-magnet acts this important part, proving how well speculations of the most profound theories lead to practical applications of the highest social utility. Hereafter we shall do justice to the inventors of the system who have effected this almost instantaneous mode of communication of thought; but the names of Volta, Ampère, Oersted, and Arago must be held up to the gaze of the civilized world; for it is these celebrated men who discovered the principles which have rendered this wonderful invention possible.

CHAPTER VI.

PHENOMENA OF INDUCTION.

Discovery of induction by Faraday—Induction by a current; inducing coil and induced coil—Induction by a magnet—Machines founded on the production of induced currents—Clarke's machine—Ruhmkorff's machine—Commutator—Effects of the induction coil.

FARADAY, one of the greatest physicists of our century, in November 1831 discovered a remarkable fact connected with the electric current; he found that when a current ~~passes~~ through a metallic wire, it produces in a second wire, placed parallel to the first, and separated from it by an insulating body, a current which flows in a contrary direction to the first current. The existence of the current thus developed by the influence of induction can be proved by the spontaneous deviation undergone by the needle of a galvanometer with which the wire communicates. The second current quickly ceases, although the first current continues to circulate in the principal wire; but if the latter is broken, another instantaneous current is produced in a contrary direction in the parallel wire, and again ceases immediately. The original current is called the *inducing current;* the current produced when this latter commences is the *inverse induced current;* and, lastly, the current which is developed when the induction current is stopped, is called *the direct induced current.*

Magnets, as well as voltaic currents, produce induction currents; and the same thing occurs with static electrical discharges, as M. Masson proved in 1834.

To obtain powerful induced currents a considerable length must be given to the parallel wires. The inconvenience which results from this is avoided by winding each of the wires covered with silk round a hollow cylinder of cardboard or wood. This is called a coil. The two extremities of each wire are terminated by two metallic buttons, or binding screws, fixed on one of the bases of the cylinder: these are for the purpose of placing the coil in communication either with the two reophores of a pile, or with a galvanometer. If we take two coils, one of greater diameter than the other, so that the smaller can pass within the cylindrical cavity of the larger one, and place the larger, or induced, or *secondary coil* in communication with a galvanometer, and the other, the *inducing coil*, into the first; and if now the latter is placed in communication with the poles of a Bunsen element, we observe that, so soon as the current is closed, the needle of the galvanometer is deviated, because an inverse induced current has traversed the wire of the first coil; but the needle soon returns to zero after slight oscillations, and remains there so long as the current passes. If the induction circuit is now broken, the needle deviates in a reverse direction, consequently indicating the presence of a direct induced current. Then it again returns to zero and stops there until the current is broken. The same experiment may be made in another manner.

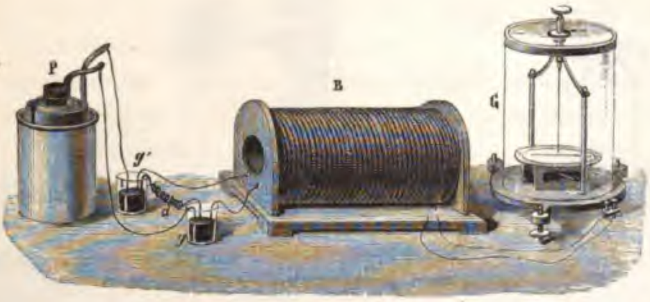

FIG. 427.—Induction by a current.

Let us suppose two copper wires wound on the same coil, well insulated from each other by the silk by which they are covered (Fig. 427): the one communicates by its extremities with a galvanometer G; the other with the element P of a Bunsen battery. The current which traverses the coil can be interrupted or established at will by raising portions of the wire which are immersed in the vessels *g* and *g'*, filled with mercury. Now, it is easy to prove, by observing the direction of the deflection of the galvanometer, the presence of induced currents, direct and inverse, at the moment when the inducing current commences and ends.

The first experiment proves that every voltaic current develops, at the moment of its commencement, an inverse current in the wire near to it; and at the moment when it ends a direct current; so that its inducing action is *nil* during the whole time the induction current is passing.

Let the induction coil be in connection with the pile, and the circuit closed before the two coils are brought together, as in Fig. 428; if now the inducing and induced coils are quickly brought near each other, an inverse current is produced in the latter, as the deflection of the galvanometer needle indicates. This current quickly ceases; but if then the induction coil is removed, a direct induced current is developed, and ceases immediately like the first. In a word, everything occurs as in the first experiment.

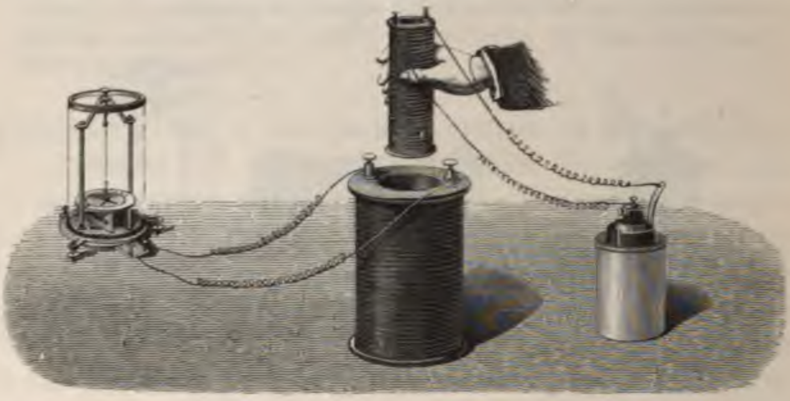

FIG. 428.—Induction by the approach of a current.

If the intensity of the inducing current is increased in the interval which separates the production of the two opposite induced currents, at the moment when this increase takes place the needle of the galvanometer, which had returned to zero, is deflected, and indicates the presence of an inverse induced current. If the intensity of the current, on the contrary, diminishes, it produces a direct current in the induced coil.

The phenomena of induction by a current may be summed up in the following statements:—

A voltaic current develops, by influence or induction, in a neighbouring inducting wire, a current of opposite direction to its own, that is to say an inverse induced current, whenever—

1st. It commences;

2nd. It approaches;

3rd. It increases in intensity.

The same current produces a direct induced current, of the same direction with its own, whenever—

1st. It finishes;

2nd. It recedes;

3rd. It diminishes in intensity.

We shall now see that the same phenomena are produced with magnetic currents, that is to say with magnets, and Ampère's theory thus received from Faraday's experiments a fresh confirmation.

Let us again take a coil, having its extremities in communication with a galvanometer, and let us place a magnet in the axis of the cylinder and quickly approach one of its poles to the coil: the needle of the galvanometer is immediately deflected and then it returns to zero. The direction of the deviation indicates a current opposite to that which, according to Ampère's theory, represents the action of the adjacent pole of the coil; moreover, the induced current soon ceases, and nothing more is manifested so long as the magnet remains present (Fig. 429). If it is removed suddenly, however, the needle of the galvanometer is deflected in a contrary direction, and then returns to zero after a few oscillations; it has thus showed the presence of a direct induced current.

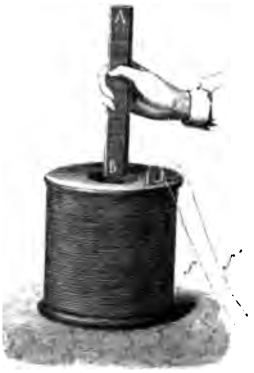

FIG. 429.—Induction by a magnet.

Before approaching the magnet let us suppose that a cylinder of soft iron has been introduced into the coil (Fig. 430). If now one of the poles of the magnet is brought near, in the direction of the axis of the cylinder, induction and the production of an inverse current will take place for two reasons: first, the presence of the magnet suffices to produce the induced current; secondly, the soft iron is itself magnetized by induction, and reacts on the coil. This is proved by the fact that the deviation of the needle of the galvanometer is stronger than in the preceding experiment. The same remark applies to the direct induced current, which the rapid removal of the magnet develops in the coil. Lastly, if the distance of the magnet from the soft iron is varied, the magnetism of this latter increases or diminishes, and the presence of contrary induced currents is proved under both conditions To sum up, an inverse current of electricity is induced in a conducting wire by a magnet, whenever—

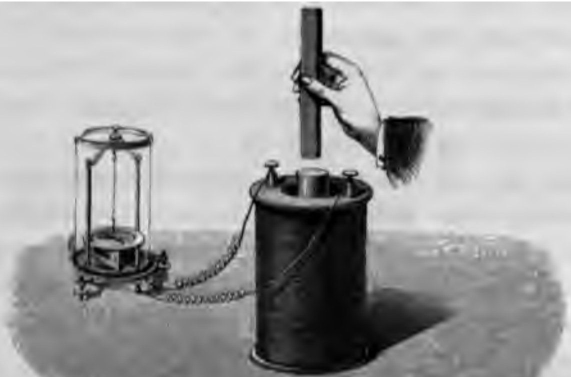

FIG. 430.—Induction by the approach or removal of a magnetic pole.

1st. The magnetic pole is approached;

2nd. It comes in contact;

3rd. Its intensity is increased.

On the other hand, a direct induced current is produced whenever—

1st. The magnetic pole is taken away;

2nd. It is detached;

3rd. Its intensity diminishes.

The magnetic power of the terrestrial globe, like a magnet, develops induction currents, and the same thing occurs in the case of static electrical discharges.

Induced currents are distinguished from ordinary currents produced by a single pile by their tension, which is much more considerable than that of the inducing current. They have been utilized in the construction of electro-motive apparatus of great power. We may mention Clarke's machine and the coil, the invention of which is due to M. Masson, but which, having received important additions from M. Ruhmkorff, now bears the name of that celebrated instrument-maker.

Clarke's machine is represented in Fig. 431; it consists of a powerful magnet, A B, composed of several plates in the form of a horse-shoe solidly fixed to a vertical piece of wood, in such a manner that its two poles are brought opposite to two coils, each furnished with a cylinder of soft iron.

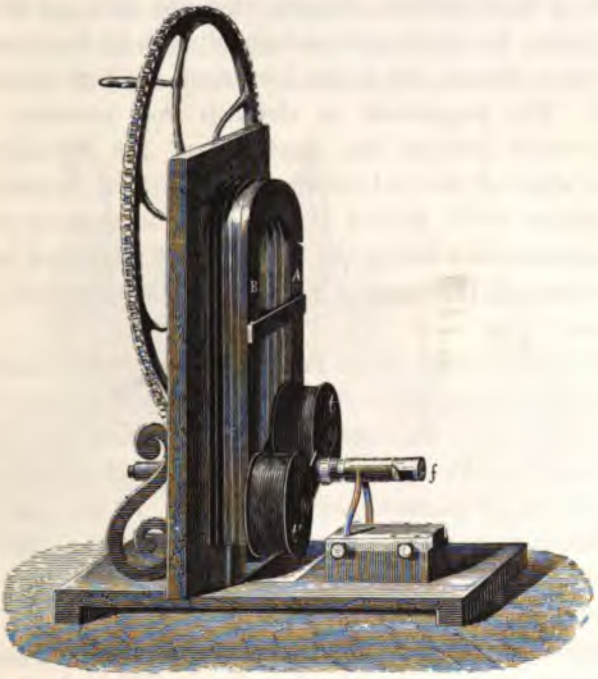

FIG. 431.—Clarke's magneto-electric machine.

The two soft-iron cores are connected on the side of the magnet by a copper plate, and on the opposite side by an iron plate, *t t'*; the two coils thus arranged constitute in fact an electro-magnet. They are arranged so as to revolve round a horizontal axis, *f*, which passes between the arms of the magnet, and is connected behind the vertical plate with an endless chain and wheel with a handle.

When the machine is put in motion, the two coils turn round their common axis, and each of them is presented at each revolution to the poles of the fixed magnet, A B. As the wires of which the coils are formed are wound in contrary directions, one of them being sinistrorsal and the other dextrorsal, it follows that the induced currents, developed in each of them by the approach of the two contrary poles of the fixed magnet, are in the same direction. The direction of these currents changes when the coils get further from the two poles; but it changes in both of them at the same time, so that, at each instant, the induced currents are both direct or both reversed. The magnetism of the soft iron moreover produces currents which increase the intensity of the inductive action. The two wires of the coil terminate at a special apparatus called a commutator, which is used at will, either to preserve the current in the same direction during the whole of the movement, or to allow the direction of this current to change alternately at each half revolution.

With Clarke's machine all the effects of ordinary electro-motors are produced, but at a much greater degree of tension than that produced by piles. Special arrangements permit the production, sometimes of violent shocks, sometimes of sparks or heating effects, and sometimes of chemical decompositions. In the last case, the current remains practically constant; in the others, on the contrary, the current must be alternately closed and broken.

Ruhmkorff's induction machine is represented in Fig. 432. It is composed of two coils: the interior one, formed of wire of a diameter of about 2 or 3 millimetres but of small length, 50 or 60 metres for instance, is the inducting coil; the two extremities of the conducting wire terminate at *f* and *f′* in two little brass binding screws.

The induced or secondary coil surrounds the first, which is placed concentrically in its cavity; it is formed of an extremely fine wire, about a quarter of a millimetre diameter, and a length of sometimes 30 kilometres. The two extremities of the induced wire are attached at the outside to two metallic binding screws, A and B, which are at the top of two insulating glass columns. Lastly, in the interior of the inducing or primary coil a cylindrical bundle of thick soft-iron wires is placed, terminated at the extremities by two discs of the same metal.

Whenever the current of an electro-magnetic machine or voltaic pile is sent through the inducing wire and traverses it, entering at *f* and coming out at *f'*, an induced current will be generated in the wire of the outer coil, under the double influence of the inducing coil and the magnetism of the bundle of soft iron. Whenever the inducing current is interrupted, it will produce in the induced coil a fresh current of contrary direction to the first. Multiplying the number of the passages of the current and its interruptions, a series of instantaneous currents will be produced, so near together and so intense, that the resulting effect will be superior to that of the most powerful batteries. It remains for us to state by what mechanism these successive interruptions are obtained.

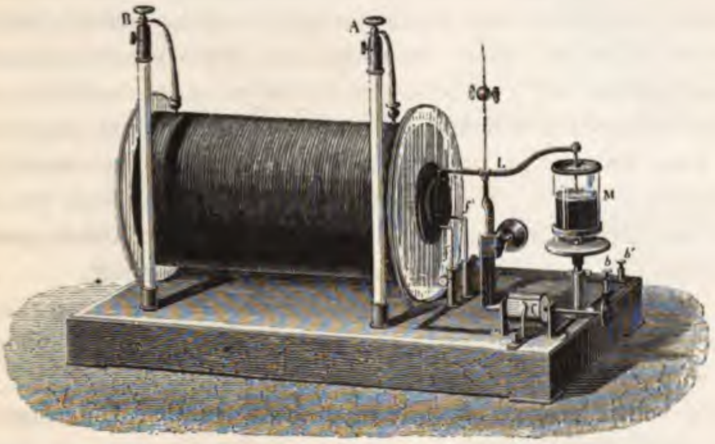

FIG. 432.—Ruhmkorff's induction coil.

At L we observe, mounted on a metallic column, a metal lever having two branches, one of which has a point on a level with the surface of the mercury contained in a glass, M, whilst the other is terminated by a piece of soft iron, reaching to within a short distance of the bundle of iron wires of the induction coil. When the point touches the surface of the mercury, the piece of iron of the other branch is no longer in contact with the iron core;

and the reverse of this happens when this latter contact takes place e point no longer touches the mercury. Let us start from the first position and notice what happens in the apparatus. The c ent of the pile then passes through the column which ca he glass filled with mercury, follows the liquid, the point in c t with it, and the branch L of the lever descends along the mn which supports it, and by means of a metallic band enters wire *f′* of the induction coil. The current then passes through induction coil, returns by *f* and passes to the other reophore of the pile; thus the contact of the point with the mercury allows the induction current to pass. But directly this current enters the coil, the bundle of soft iron is magnetized, attracts the small mass of the lever, whence results the raising up of the branch carrying the point; this leaves the surface of the mercury, and the current is broken. Then the magnetism of the bundle ceases, the contact of the piece of soft iron no longer exists; and the point again touches the mercury. The same phenomena are produced in the same manner, as long as the induction coil is in communication with the pile. The mercury contact-breaker which we have just described was invented by M. Léon Foucault. Other contact-breakers produce the same effect by means of a spring.

We have said nothing at present about the commutator, *c*, the object of which is either to change the direction of the induction current, or to interrupt it. Ruhmkorff's commutator (Fig. 433) fulfils both functions at will: it is both *rhcotome* (interrupter of the current) and *rhcotrope* (inverter of the current). It consists of a cylinder of wood or glass, the convex surface of which is partly covered with two copper plates, C C′, thick in the middle and thinner at the edges. These plates have intervening between them two portions of the surface of the insulating cylinder; on each side two springs, *f f′*, press laterally against the cylinder, when it is turned so as to bring the thickness of the copper plates in contact with the springs. If, by the use of a milled-head or a handle with which its axis is furnished, the cylinder is turned through 90 degrees, the plates of the springs are opposite the glass or wood, which they need not necessarily touch. In the first position, the current passes; in the second, it is interrupted. Indeed, the current reaches the pile with the binding screw A; thence, by the spring *f*, it passes to the copper plate C. This communicates by a screw *g* with one of the pivots of the cylinder, then with the button D, and traverses the circuit, one of the ends of which is fixed to this latter point. It returns by the other extremity to the button D′ to the second pivot of the cylinder, and by the screw *g′* to the plate C′, and lastly, by the spring *f′*, to the binding screw A′, whence it returns to the pile. When the springs *f f′* no longer touch the plates C C′, the current can no longer pass. This apparatus is then a good interrupter or *rheotome*.

But when the current passes as we have just stated, it is sufficient to turn the button through 180°, to change its direction. For then, the plate C′ touches the spring *f*, and the current passes from D′ to D, instead of going from D to D′. Thus the little apparatus of Ruhmkorff is also a *commutator*, that is to say, an *inverter* of the current, or *rheotrope*. It forms part of the induction coil; but it is clear that it can be used whenever we require to change the direction of a current.

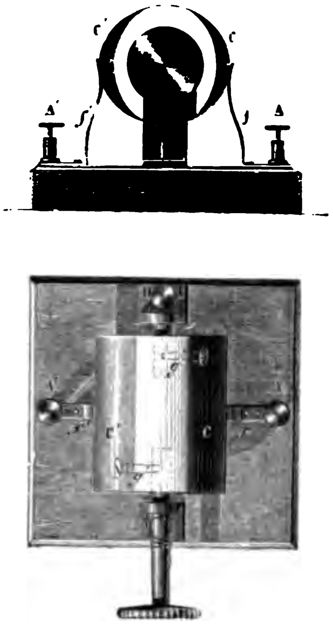

FIG. 433—Commutator of Ruhmkorff's machine. Plan and elevation.

When Ruhmkorff's coil is at work, if the two extremities of the wire of the induced or secondary coil are brought sufficiently near, a series of sparks succeed each other with such rapidity that the line of light appears continuous. It is remarkable that, of the two induced currents opposite in direction which are generated by successive interruptions of the inducing current, the direct current alone produces sparks; the tension of the inverse current is not sufficiently strong to allow it to traverse the air.

With the first coils, the length of the sparks attained a maximum of 8 millimetres. By degrees, improvements—among which we must point out that of M. Fizeau, which consists in interposing a condenser, a Leyden jar for example, in the circuit—have led to the production of sparks from 10 to 20 and 30 centimetres. By increasing the length of wire of the induction coil to 100,000 metres, M. Ruhmkorff was able to obtain sparks of 50 centimetres in length: blocks of glass one decimetre in thickness have been pierced through and through by the discharge. The physical effects obtained with this powerful machine are extremely remarkable: we may employ it to charge Leyden jars and electrical batteries. It is thus that M. Jamin, having charged a battery of 120 Leyden jars with four coupled coils, each furnished with two of Bunsen's elements, was able to melt and volatilize iron, silver and copper wires, more than a metre in length.

CHAPTER VII.

THE ELECTRIC LIGHT.

Sparks obtained by static electrical discharges; luminous tufts—Light in rarefied gases—Voltaic arc; phenomena of transport; form of the carbon points—Intensity of the electric light—Electric light of induction currents—Stratifications; experiments with Geissler's tubes—Phosphorescence of sulphate of quinine.

BETWEEN the feeble sparks seen in the darkness, when the finger is brought near a rod of resin which has been rubbed with a piece of cloth, and the long and bright flashes of fire which are emitted by the conductors of powerful batteries, or by the dazzling light of the voltaic arc, there is indeed a difference: it is, nevertheless, the same phenomenon. It is also the same light which appears with greater beauty and grandeur in thunderstorms.

Let us inquire into the circumstances under which this light is produced. We have seen that, whenever two bodies charged with opposite electricities, at a sufficiently great tension, are near together, with a non-conducting interval,—that is, when a resisting medium is interposed between the two bodies,—a spark passes. The tendency which contrary electricities possess to unite and constitute a neutral electricity, when they find themselves prevented by the resistance of a non-conducting medium, leads to this transformation of the forces, a transformation of electricity into light and heat. Hence the spark in all its forms.

These varied appearances we shall now review, both in the case of the discharges of static electricity, of electricity at high tension, and in dynamic electrical currents, which the voltaic pile and induction apparatus have developed to so high a degree of power.

With ordinary electrical machines of large dimensions remarkable luminous effects may be produced. For this purpose a metallic plate is employed, which is held in the hand by an insulating handle, and is joined by means of a metallic chain to the friction cushions.

By bringing the edge of the plate of the conductor of the machine to different distances, the spark will at first be seen under the form of a rectilinear line of light, of a dazzling whiteness and brightness. If the tension of the conductor is increased by turning the handle of the machine without interruption, the sparks succeed each other with so much rapidity that the line of light appears continuous. The sparks get thinner at their centre, in proportion as the distance of the two conducting bodies increases, and the rapidity of their succession diminishes; then their rectilinear form gives place to lines more or less zigzag, or serpent-like in form, as if the resistance which the flow of the electricity undergoes in its passage was unequally distributed.

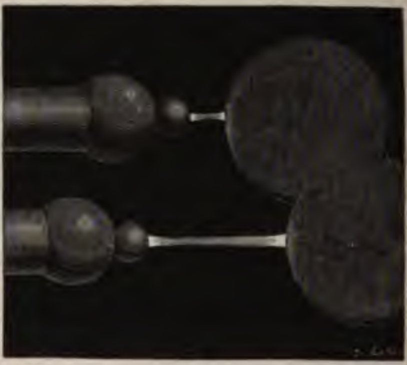

FIG. 434.—Sparks obtained by the discharge of static electricity.

Besides the principal line of light, we perceive, when the distance becomes still greater, luminous branches which issue on all sides, and give to the sparks the forms represented in the drawings of Fig. 435. These long branch sparks are evidently the form of transition between the rectilinear spark and the luminous brushes. To obtain this last form of electrical light produced from the conductors of ordinary machines, the metallic plate must be presented at a much greater distance than when the sparks we have first described pass from the conductor. Then there appears to escape from the conductor a kind of luminous tree which touches the conductor with its trunk,

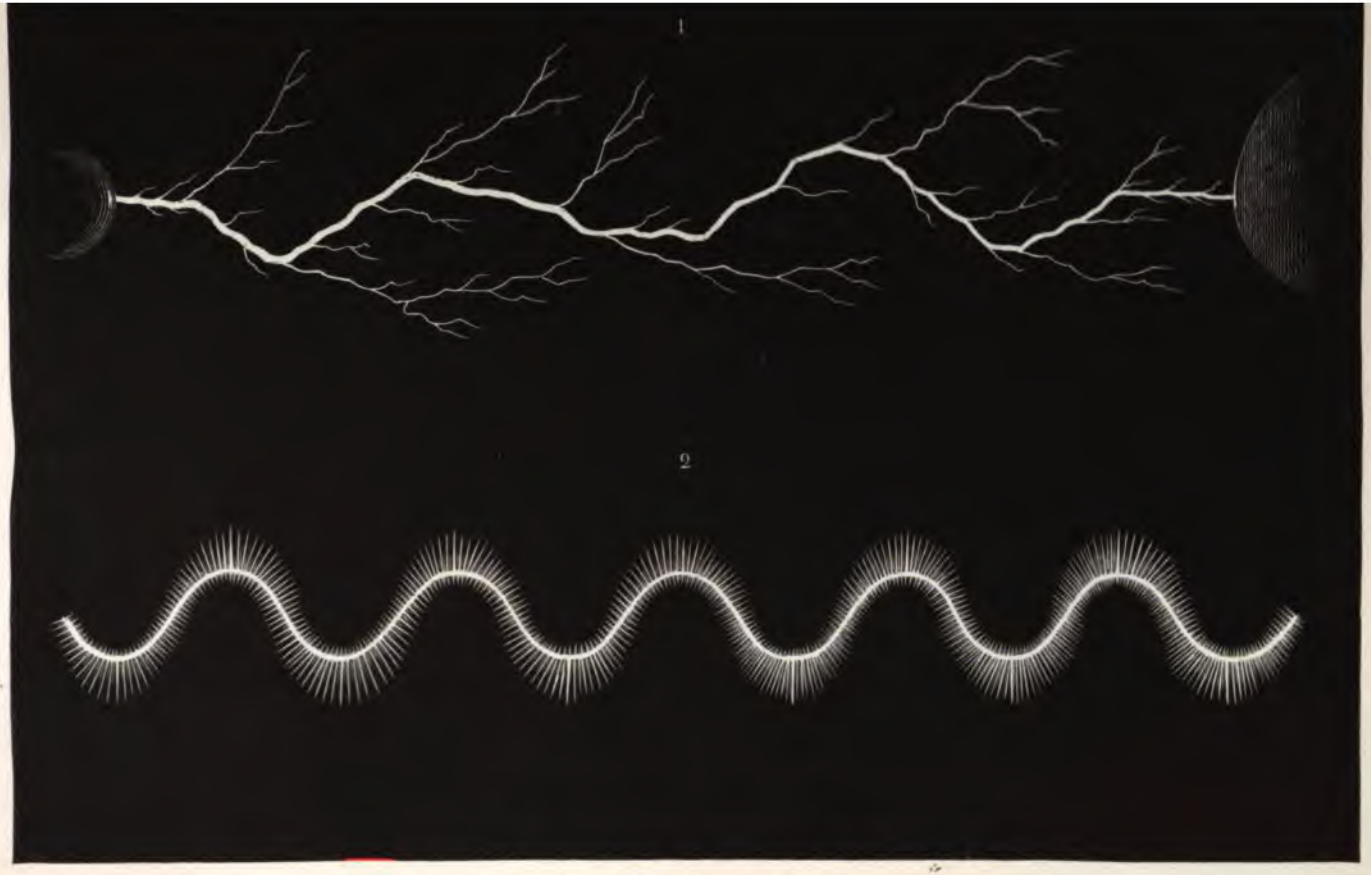

FIG. 435.—Forms of electric discharges (Van Marum).

while an infinite number of branches diverges towards the plate. Fig. 436 shows a luminous tuft as obtained by Van Marum. Between the plate and the brush there sometimes exists a dark space; sometimes a mass of light, very narrow and having its base on the edge of the plate, joins the top of the brush. In this case, we suppose that the conductor is charged with positive electricity, and the plate electrified by induction is, therefore, charged with negative electricity. If the reverse took place, the brush with wide ramifications would escape

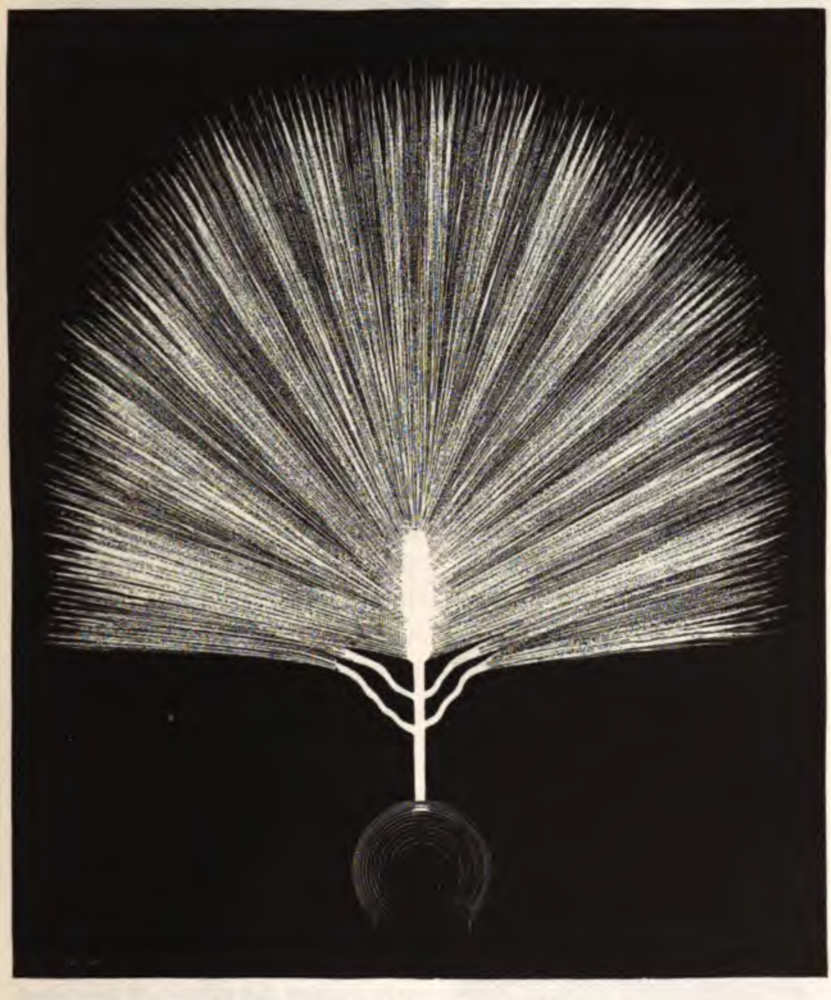

FIG. 436.—Electrical brush, according to Van Marum.

from the plate and the narrow end from the conductor. Faraday, who studied the forms of positive and negative brushes, showed that this difference results from an unequal tension of the two electricities when the discharge takes place. Negative electricity requires for its discharge a much less tension than positive electricity.

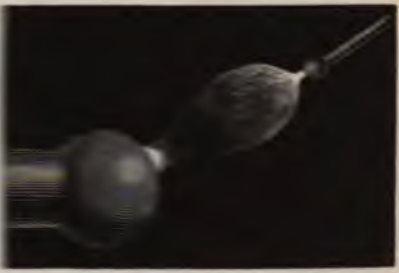

Fig. 427.—Positive and negative brushes.

The electric light can be produced in different media, in air and other gases, and even in bad-conducting liquids: its appearance, that is to say, its form and colour, changes according to the nature of these media; and when the discharges take place in a gas, they vary with its pressure or degree of rarefaction. In air, at ordinary pressure, we have seen that the spark is a brilliant white. According to Van Marum, who made numerous experiments on this subject, its colour is bluish, tinged with purple, in nitrogen; very white in oxygen; violet red in hydrogen; greenish in carbonic acid; reddish-green in carburetted hydrogen gas, and white in hydrochloric acid.

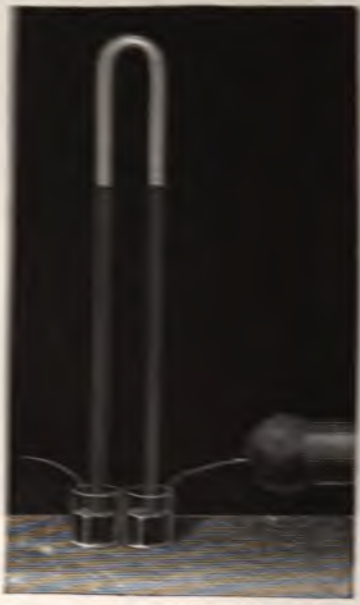

Fig. 428.—Light in the barometric vacuum.

The trunk of the positive luminous brushes in air, at the ordinary pressure, is of a violet colour, tinged with purple, whilst the branches are white,—this is perhaps because the light is less condensed. In other gases the colour of the brush varies, as Faraday's experiments showed: thus, in hydrogen and in coal gas, it is slightly greenish; in oxygen it is white as in air, but much less beautiful; in rarefied nitrogen, it is, on the contrary, a magnificent purple; in carbonic oxide and carbonic acid it is greenish in the first gas, and slightly purple in the second. In the barometric, or Torricellian vacuum, there is no spark, or rather the spark appears between the conductor and the metallic wire which dips in the mercury: at this moment, the barometric vacuum is illuminated with a greenish light, as in Fig. 438.

For the study of the luminous effects produced by electrical discharges in rarefied gases, the apparatus represented in Fig. 439 is employed: this is called an *electric egg*. The two metallic rods, each terminated by a ball, and communicating with the conducting caps of the apparatus, can be approached or separated at will. The egg can be detached from its stand and screwed on the plate of an air-pump, so that the air can be rarefied at will, a vacuum made, and a gas introduced at any pressure.

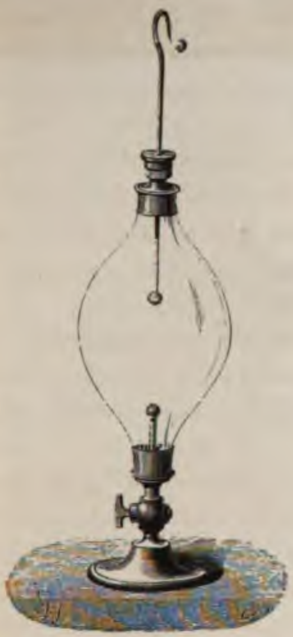

FIG. 439.—The electric egg.

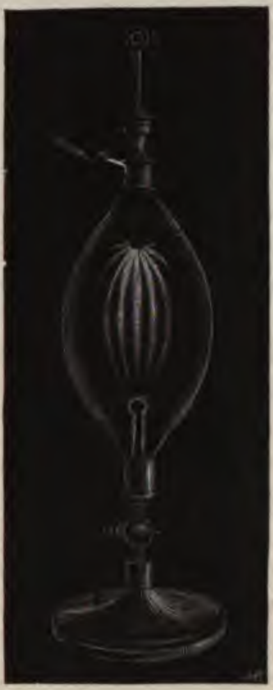

FIG. 440.—Electric light in rarefied air. Purple bands.

In air, at ordinary pressure, the spark obtained between the two balls is similar to that we have described at the beginning; but in proportion as the air is rarefied, the light changes in appearance and escapes from the positive ball as a branched sheet; at a pressure of 60 mm. it presents the appearance shown in Fig. 440. It then appears to be composed of a number of luminous bands of a purple colour, some diverging laterally, others terminating at the negative ball, which is itself enveloped in a thick sheet of violet light. When the pressure is reduced to a few millimetres, the bands unite into a luminous sheaf, in the form of a spindle.

The various luminous phenomena we have just described are produced by static electrical discharges. Between the two approximated ends of the reophores of a pile with a very large number of elements, brilliant sparks may be obtained which succeed each other with rapidity. We have stated above that the phenomenon is much finer, and the light more intense, when it is caused to pass between two carbon points terminating the extremities of the reophores: we then obtain what is called the *voltaic arc.* By making use of induction currents, extremely remarkable luminous effects may be obtained without the necessity of a pile with a great number of elements. The following are some details of the voltaic arc:—

We have already said that, in order to produce the luminous arc, it is necessary to place the carbon points very near to each other; but when once the current has conquered the resistance of the interposed air and produces the light, the points can be further separated: Davy, working in rarefied air, obtained with his pile of 2,000 couples an arc of light of eighteen centimetres in length. The luminous intensity of the voltaic arc is so considerable that the eye can scarcely endure its brightness. According to some experiments made by MM. Fizeau and Foucault, this intensity is nearly fifty times greater than that of Drummond's light,—that is, the brilliant light produced by directing an ignited jet of oxy-hydrogen gas on a piece of lime; solar light has scarcely an intensity triple that of the voltaic arc. These two experimenters worked with a Bunsen's battery of 92 couples arranged in two series.

In studying the very interesting phenomenon of the voltaic arc, it has been noticed that the electrical current passing continuously between the two points transports from one to the other minute particles of carbon: this transport of matter is made with greatest eadiness from the positive to the negative pole, so that the points ecome unequal in size: the negative point increases at the expense f the other. Fig. 441 shows the appearance of the two points, as een by projection on a screen, in an enlarged form. We will leave he description of it to the learned physicist to whom we owe this drawing. M. Le Roux, in a conference on the application of electricity to lighthouse illumination, given by him at the *Société d'Encouragement pour l'Industrie nationale,* described it as follows:—"In order to directly examine what passes in the voltaic arc, great care must be taken to place the eye in

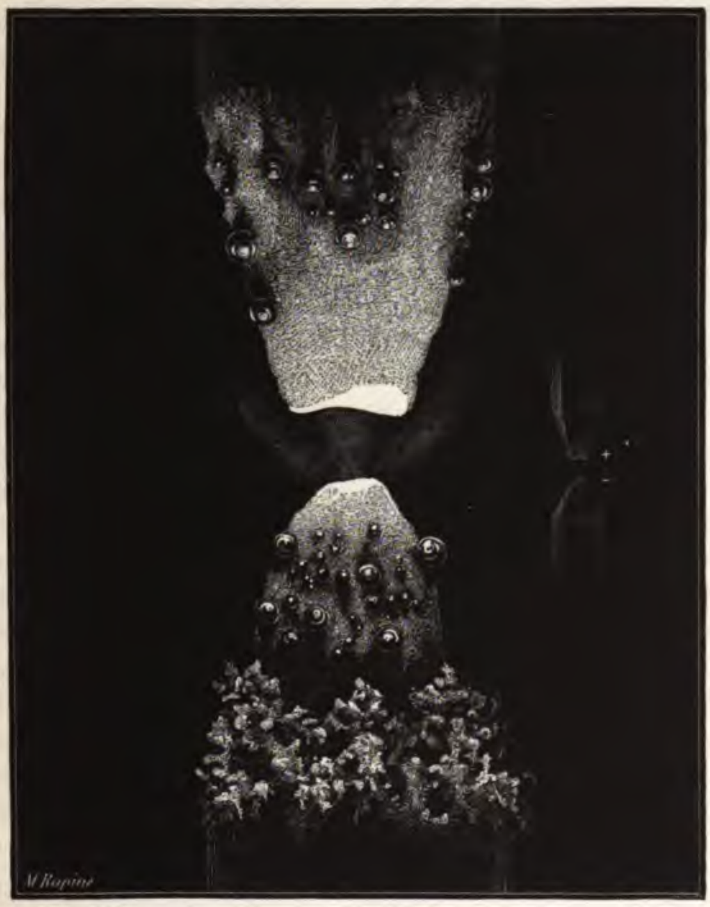

FIG. 441.—Carbon points of the electric light and the voltaic arc between them.

safety from the considerable intensity of the light, but
same intensity allows us to observe the whole of the smal
details of the carbon surfaces. It is sufficient to interpose
tween them and the screen a lens with a proper focus: you
then perceive the image of the carbon points enlarged a hund
times; this projection enables you to examine, without fatigue,
whole of the phenomena. Here are some carbon points betw
which the continuous current of a Bunsen's pile passes. You
one of the points increases at the expense of the other: this
which is the most used, is the positive point; it is this wh
communicates with the carbon end of the pile; if it is more poi
than the other, it is because it loses material which the o
acquires. We can, indeed, reverse the direction of the current:
then see the carbon point which was just now the most poin
increases, whilst the other becomes more slender; besides, from t
to time some larger patches detach themselves, traverse the sp
under the form of little incandescent masses, and indicate the di
tion of transport. You see little globules boil up here and th
on the surface of the carbon; these are globules of melted sili
you will remark that these globules do not appear on the car
points where the temperature is highest; they are volatilized at
outset. Now we are in a very impure vein, and a considera
quantity of these silica globules show themselves; the brightnes
the arc suffers; blowing lightly against the carbons, the curren
air inclines the arc and shows us its development. We now re
a part of the carbons where their purity leaves nothing to be desi
You see how quiet the arc is, the progress regular, the points cle
terminated. You will see the quiet, bluish light of the arc contr
ing with the bright white of certain parts of the points; the
forms a kind of truncated cone swollen in the middle, the two ba
of which are the carbons: these two bases are the brightest p
tions, the temperature is the highest in them, the molecules tra
ported by the current strike them."

When a space filled with gas or very rarefied vapours
traversed by induction currents, the luminous effects present p
ticular characteristics of great interest.

If the air contained in an electrical egg is rarefied to a press of two or three millimetres, and if the interior balls are placed in communication with the poles of a Ruhmkorff's coil, a magnificent luminous sheaf is seen, of a beautiful red, starting from the positive ball, whilst the negative ball and rod are enveloped in a sheet of light of a bluish purple. If the direction of the current is reversed with a key, or commutator, the two lights are inverted; the sheaf issues from the lower ball, whilst the violet aureola envelopes the upper ball. If, before rarefying the air, vapours of different substances are introduced,—for example, alcohol, phosphorus, or essence of turpentine,—the luminous sheaf assumes a particular aspect which was discovered nearly at the same time by Ruhmkorff, Grove, and Quet. The red light of the sheaf is interrupted transversely by very narrow dark bands, so that it is alternately formed of dark and bright striæ. From the middle of the sheaf, where the striæ are rectilinear, they are curved in two opposite directions, each facing the balls concavely

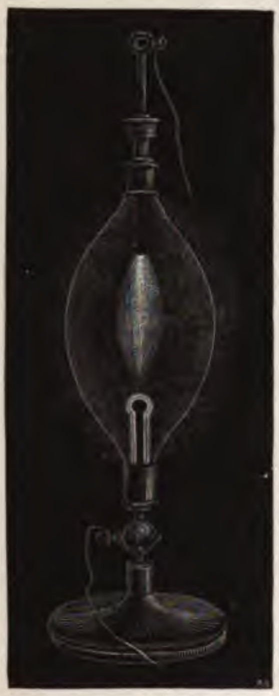

FIG. 442.—Luminous sheaf in rarefied air. Discharge of induction currents.

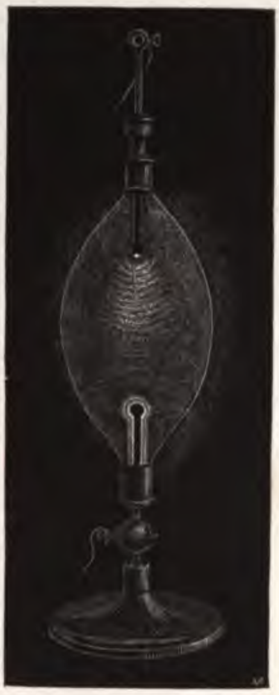

FIG. 443.—Stratified light in rarefied gas.

To this phenomenon is given the name of *stratification of the electric light.*

Since the time of this discovery, different forms have been given to the vessels which contain the rarefied vapours suitable for the production of the stratifications. Plate X. (the various drawings of which have been made from the objects themselves) reproduces some of the most curious effects of this kind, produced in tubes known as *Geissler's tubes.* The beauty of these luminous effects is again enhanced by the phenomena of phosphorescence which the electric light produces in uranium glass, and in certain salts (notably sulphides), of strontium and calcium, and also in sulphate of quinine.

THE ELECTRIC ARC

IN RAREFIED GASES

1. Luminous stratifications in alcool vapour.—2. Phosphorescence of sulphide of calcium.—3. Stratifications in Geissler's tubes
4. Fluorescence of uranium glass.—5 Phosphorescence of sulphide of strontium—6. Fluorescence of uranium glass & sulphate of quinine

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BOOK VII.

ATMOSPHERIC METEORS.

BOOK VII.

ATMOSPHERIC METEORS.

Optical meteors: mirage, rainbow—Tension of aqueous vapour in the atmosphere; hygrometry—Clouds and fogs—Dew, rain, snow—Crystals of snow and ice—Variations of barometric pressure—Measure of maxima and minima temperatures—Electrical meteors; thunderbolts, thunder and lightning—Auroræ boreales.

THE reader who has occupied himself with the studies of which we have spoken at some length, though in a very incomplete manner, will find that all the physical phenomena of nature arrange themselves in one or other of the categories which correspond to the six Books of this work: Weight, Sound, Light, Heat, Magnetism, and Electricity. We have seen moreover that electricity and magnetism have the same cause—that they are, in fact, two modes of action, at first sight different, but really the same, resulting from the same physical agent. The more science advances, the more are the divisions of which we speak effaced; in other words, the more evident does it become that one principle will probably some day or other account for the varied phenomena perceived by our senses, and of which the world presents a perpetual development. Moreover, in nature these phenomena are not isolated: the separation which science is obliged to make, without which separation indeed science would not be possible, does not exist in reality; not only do the phenomena co-exist, but they act and re-act one on the other; they strive with, interpenetrate, and modify each other in a thousand different ways, and these are the innumerable actions which become to the observer or contemplator of the universe the source of all the contrasts and of all the harmonies which he observes.

In this concluding Book it is impossible to present a sketch of the immense picture—the magnificent panorama which results from the concourse of physical phenomena; but we cannot omit showing the ties by which some of them are bound to the facts which we have studied, and which the physicist reproduces on a smaller scale in his laboratory. Let us for this purpose consider some of those phenomena which are called atmospheric, the place of their production being the aërial envelope with which the terrestrial globe is surrounded. They may be arranged in three principal classes: *luminous or optical meteors; aqueous meteors*, the production of which is due to the modification undergone by aqueous vapour under the influence of variations of pressure and temperature; and lastly, *electrical or magnetic meteors.*

The refraction of the luminous rays which have to pass through either the entire strata of the atmosphere, or a part of them, gives rise to numerous phenomena, amongst which we have already described the apparent elevation of objects above their real position, which is called atmospheric refraction. *Mirage* is a phenomenon due to the same cause; it is observed chiefly on the surface of plains of sand, when the ground has been strongly heated by the sun's rays. The traveller who crosses these plains, then sees objects which are raised above the ground, reflected as if on a liquid expanse; the illusion is so strong that those who are, for the first time, witnesses of the phenomenon, cannot help believing in the real existence of a lake spreading its waters along the horizon. The French soldiers in the Egyptian expedition were more than once deceived by this false appearance. Overcome with fatigue and thirst, they saw the longed-for lake recede as they approached, renewing for them, under a form not less deceptive, the tortures of Tantalus. Monge, one of the men of science of the Egyptian Institute, was the first to give a complete explanation of the mirage, which, however, is not alone observed in the African deserts.

The following is his theory of the mirage. The solar rays, on reaching the surface of the sandy stratum, heat it strongly, whilst they have passed through the superposed strata of air without much raising their temperature,—the absorbing power of gases being very small compared with that of solids. But the heat of the ground is

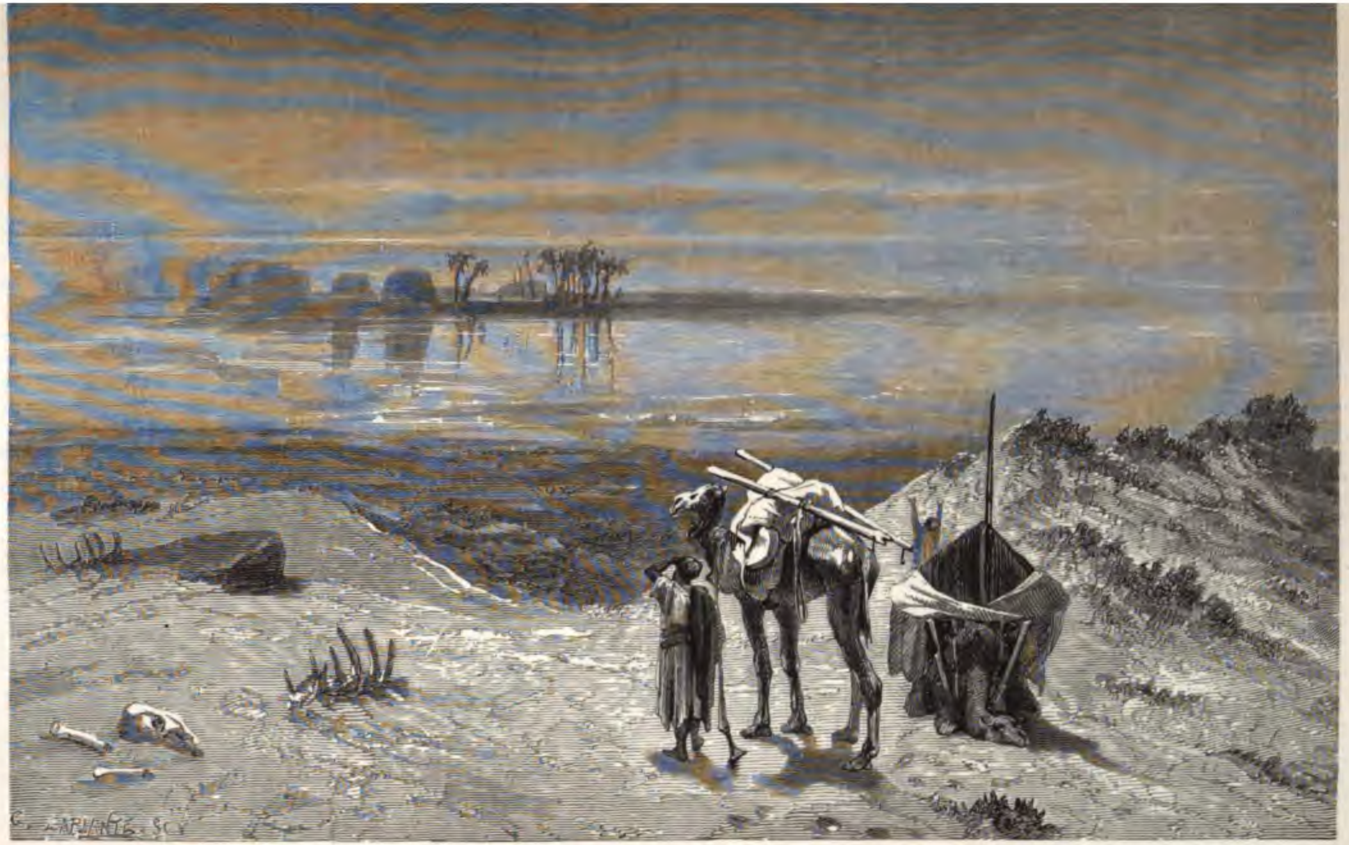

FIG. 444.—The Mirage in the African Desert.

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communicated by direct contact to the lowest stratum of air and from that successively to those above it; and expanded air rises in virtue of its specific lightness; but if the ground presents a nearly horizontal level, and if the atmosphere is calm, equilibrium is retained, and feeble currents produced by some inequalities in the expansion of the different portions of the lower air are alone produced. Hence it follows that, towards the middle of the day, the strata of the air nearest the ground are arranged, from top to bottom, in the order of decreasing density. Let us now imagine a luminous beam sent obliquely to the ground from the point M, a tree in our sketch (Fig. 445); on passing from the rarer into the denser stratum, it will deviate from the vertical, from *a* to *d*, and this deviation will increase in proportion as it encounters strata more and more refractive, until falling at A on a stratum with the surface of which it makes an angle equal to its limiting angle, it will undergo total reflection. Starting from this point, it will follow a contrary path, getting nearer and nearer to the vertical, falling on O in the observer's eye, who then sees an image of the point M in M′. The same path being applied to all the points of the object—here it is a tree,—it will appear reflected as in a mirror, and the observer will see it as a reversed image. The sky is reflected in the same manner, whence the brilliancy of the ground at a certain distance from the object, and the appearance which causes the belief in the presence of a liquid between the eye and the object.

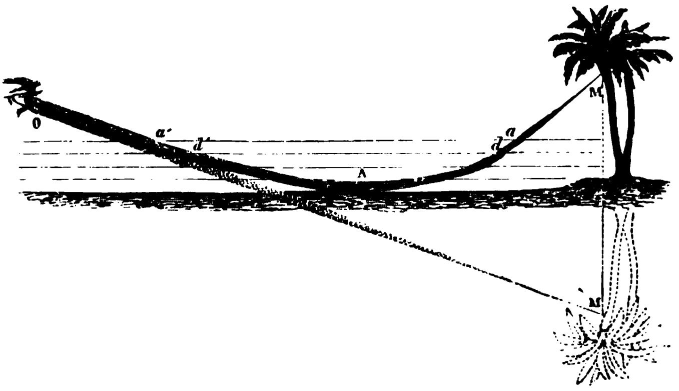


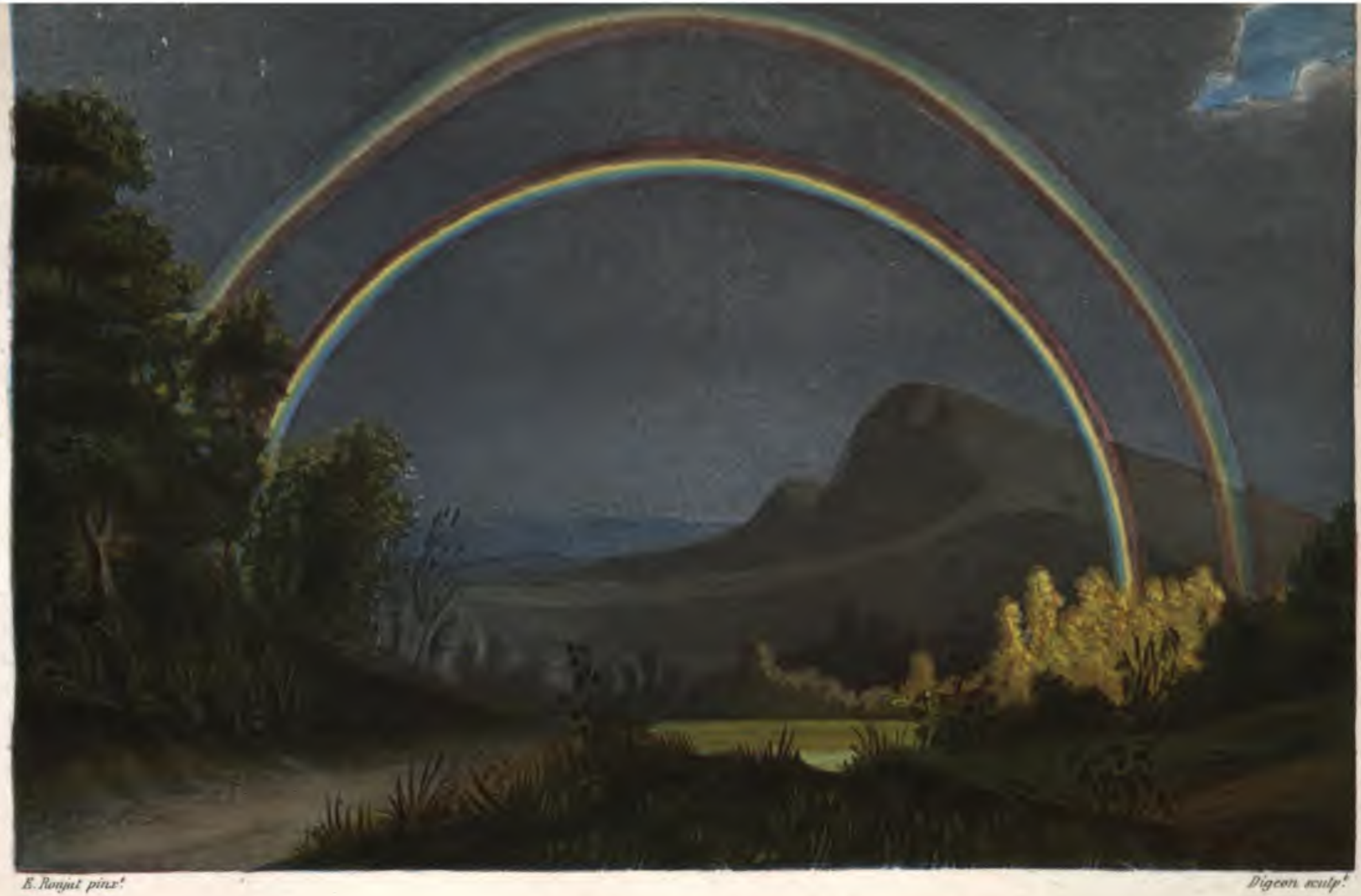
FIG. 445.—Explanation of the mirage.

The phenomenon of the mirage takes place also on the surface of the sea, when the water has a higher temperature than that of the air, and the explanation is the same as that of the mirage on land.

When the strata of the air are unequally heated, instead of being separated by horizontal surfaces, they are more or less oblique, and we get the *lateral* mirage which is observed principally in mountainous countries, or in the vicinity of buildings: in this last instance, the objects appear reflected as in a vertical mirror. It even happens, as is sometimes observed at sea, that the mirage of the object, as a vessel for instance, is formed above it. The son of a celebrated navigator and physicist, Scoresby, witnessed in the polar seas this last phenomenon, which was then called the *inverted mirage*. One day he perceived in the air the inverted image of the ship which his father commanded, and from which a sudden storm had separated him, and the image was so clear that he could recognize the vessel, although it was completely hidden below the horizon. To explain this phenomenon, the existence of horizontal strata of air, the density of which rapidly diminishes from below upwards, must be supposed at a certain height in the atmosphere.

The mirage is a phenomenon of simple *refraction*. The *rainbow*, *halos*, and *parhelia* are luminous meteors produced by the *dispersion* of light during its passage through rain-drops, the very small drops of which form the clouds or haze which float in the atmosphere. We shall confine ourselves to a statement of the theory of the rainbow, propounded by Antonio de Dominis in 1611 elaborated by Descartes, and lastly perfected by Newton.

We all know that the rainbow or iris is seen opposite to the sun, through the clouds which are turned into rain, and that it is sometimes simple and sometimes accompanied by an outer bow less brilliant than the first. The principal or interior bow forms a circular band in the width of which the various colours of the spectrum are seen in order from violet to red, starting from the inside of the bow. The secondary bow is wider than the first and shows the same colours arranged in a reverse order, so that the red is inside, next to the red of the principal bow. Plate XI. shows this arrangement and gives an exact idea of the width and relative bright-



E. Roujat pinxt. Digeon sculpt.

DOUBLE RAINBOW

REFRACTION, REFLECTION & DISPERSION OF LIGHT

ness of the bows, as well as the apparent dimensions of the zone which separates them.

To account for the conditions which produce the phenomenon, let us trace the path of a solar ray, which falls on the surface of a spherical drop of rain. On arriving at the surface of the sphere, the luminous ray is refracted and approaches the normal at the point of incidence. On meeting the interior surface of the liquid sphere it is divided; part of it emerges and the other part is reflected. The same effect takes place at each of the meetings of the reflected ray with the surface of the drop, the intensity of the reflection diminishing in proportion as the successive reflections are accomplished. Knowing the angle of incidence of the luminous ray, the angle at which it leaves

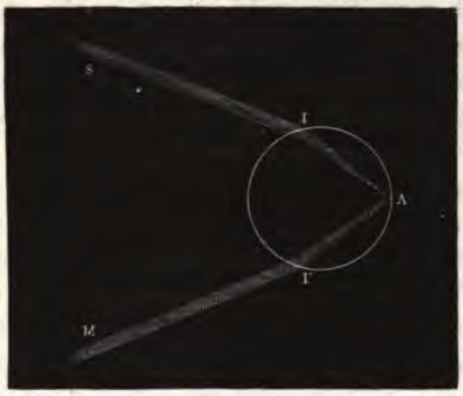


FIG. 446.—Paths of the effective rays through a drop of rain after a single internal reflection.

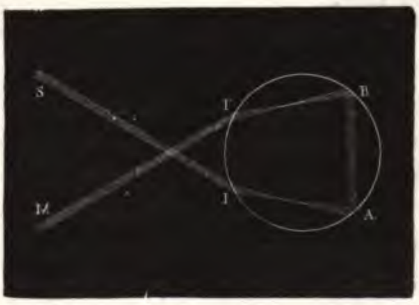


FIG. 447.—Path of the effective rays after two interior reflections.

the liquid sphere, after one, two, or any number of interior reflections, can be calculated. Instead of a single ray of light, if we imagine a beam such as S I, the angle of incidence of the rays which compose the beam, not being the same for all, the emerging rays will emerge generally in diverging from the sphere, in such a manner that if dispersed through space they could not act on the eye or produce an image on the retina at any distance. Nevertheless, calculation proves that for certain incidences the emergent rays form a cylindrical beam, the intensity of which will remain sensibly the same at a considerable distance. Newton gave the name of *effective rays* to those which possess this property.

Let us recall to mind that the different coloured rays of which a beam of white light or solar light is composed, have not the same refrangibility. The incidences which correspond to the effective rays of each simple colour are therefore not the same; hence it follows that on emerging from the liquid sphere the incident beam will be divided into as many separate rays as there are colours in the spectrum. On calculating the angles of incidence for the rays of the extreme simple colours, the violet and the red, after a single internal reflection we find:

For the violet rays, an angle of incidence of 58° 40′; for the red rays, an angle of incidence of 59° 23′.

Therefore the angles which the emerging rays make with the direction of the incident rays are 40° 17′ for the violet rays, and 42° 2′ for the red rays.

In the case of two internal reflections, in A and B the angles of incidence of the effective rays are:

For the violet, 71° 26′; for the red, 71° 50′; and the deviations undergone by the rays, after this emergence from the liquid sphere, are 50° 59′ for the red rays, and 54° 9′ for the violet rays.

By means of these data, it may be seen that the principal rainbow is produced by the solar rays which have undergone a single reflection in the interior of the liquid spheres composing the rain-drops. The exterior rainbow is produced by the rays which have passed through two successive reflections. Let O Z be a line parallel to the direction of the solar rays, and passing through the eye of the observer who turns his back on the sun. Looking in the direction O *a*, so that the angle *a* O Z is that of the deviation corresponding to the effective violet rays, the observer will receive on his eye a violet ray proceeding from the solar ray S *a*, which has been once reflected in the rain-drops, when they pass successively in their fall by the point *a*. Indeed the parallelism of the lines O Z and S *a* conduces to the equality of the angles S *a* O and *a* O Z; now this last is by hypothesis equal to the angle of deviation which corresponds to the effective violet rays. The ray S *a* will then find a rain-drop, whose position will be that which agrees with the calculated incidence and emergence; and the eye will see a violet point. About 2 degrees higher, at *b*, he will see a red point, and in the interval *a b* all the shades of the spectrum comprised between the violet and the red; that is to say, indigo blue, green, yellow, and orange. But the same thing will evidently occur in every direction making with O Z the same angles as those of which we have spoken. The observer will then see bands of all these colours, projected on the sky under the form of concentric circles having their centres on the line O Z, in a point diametrically opposite to the sun. So much for the solar rays which penetrate the rain-drops and emerge after a single reflection. Those which have undergone two reflections will arrive at the eye forming with the line O Z angles of 50° 59′, if they are red rays, and 54° 9′ if they are violet rays.

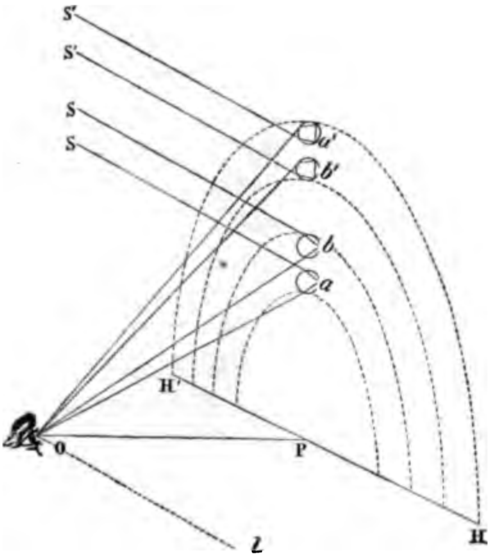


FIG. 448.—Theory of the rainbow; formation of the principal and secondary arc

The effective rays of the intermediate colours will be comprised between these extreme rays; but in this case the red will be at the interior and the violet at the exterior.

These results are deduced from calculation, according to the laws of reflection and refraction of light, and the index of refraction of water. Now, the angular dimensions of each rainbow, the width of the zones, and that of the interval which separates them, are so many consequences of the preceding data, and, if the theory is correct, observation ought to verify the truth of it; and indeed the explanation of Newton, and of all observers who after him studied the rainbow, has been verified. When the sun is at the horizon, the line O Z is in this plane; the centre of the arcs is then itself at the horizon, and the rainbow is seen under the form of a semicircle; and it presents this form both at the rising and the setting of the sun to an observer situated in the plain. For different heights of the sun, the rainbow has an amplitude less than a semi-circumference, which gets less as the sun gets higher. Lastly, if the observer were situated on a very high mountain and on a narrow peak, he would be able to see more than a semi-circumference, and even a complete circle, if the rain fell at a considerable distance.

It must not be forgotten that the rainbow is a phenomenon the production of which depends only on the position of the observer relatively to that of the sun, and of the cloud which is converted into rain. Therefore if two persons at a distance from each other see a rainbow at the same time, they do not see the same arc. If this were the case, the observer situated obliquely would see it in perspective, and in the form of an oval or ellipse, not as a circle. Theory and observation agree in proving the impossibility of the fact we have just imagined. We have often heard persons, to whom we have mentioned having seen a rainbow, reply that they also had seen it; but they were mistaken, at least unless they were precisely in the same position as we ourselves were, at the same instant.

Aqueous meteors are those caused by the transformation which the vapour contained in the air undergoes, under the influence of variations of temperature. Clouds, fogs, rain, snow, dew, white frost and hoar frost, are the different forms under which the atmospheric water is presented to our view, which therefore assumes these three conditions: the gaseous condition, when it exists as invisible vapour; the liquid condition, when the lowering of temperature condenses it into drops more or less small; lastly, the solid condition, if a still greater cooling congeals the drops which then fall in the form of white flakes, or arrange themselves into crystals on the surface of the ground. The complete description and detailed explanation of these different phenomena would take us beyond the limits of our space. We shall therefore limit ourselves to an indication of the physical laws which relate to their production.

Analysis proves that the air is a mixture of two permanent gases, oxygen and nitrogen, with which variable quantities of aqueous vapour and carbonic acid are mixed. But while the proportion of oxygen and nitrogen remains constant, that of the aqueous vapour varies perpetually and depends on numerous atmospheric conditions, such as temperature, direction and force of the wind, &c.

It is very important to the science of meteorology to know how to determine, at a given instant, the hygrometric state of the air. By this term we understand the relation between the tension of the aqueous vapour, which is actually contained in it, and the maximum tension which the same vapour would possess if, at an observed temperature, the air were saturated with it.

This relation is deduced from the indications of instruments called *hygrometers*, constructed on different principles, among which we shall only describe the *hair hygrometer*, which bears the name of De Saussure, its inventor.

It is based on the property which hairs, like many other animal substances, possess, of being very sensible to variations of atmospheric dampness. A hair previously washed in sulphuric ether, which frees it from the oily matter which it contains, lengthens when it absorbs aqueous vapour and shortens when it loses the absorbed moisture. The following is the manner in which these changes of dimension are rendered sensible:—

The hair is fixed by its upper extremity, and passes round a pulley at the centre of which there is a needle moving on a divided circle. A small weight keeps it on the pulley; and as this forms with the needle a system of unstable equilibrium, the least variation in the length of the hair turns the pulley, and therefore the needle, in one direction or the other.

The hygrometer is graduated by taking, for the fixed points, the extreme dryness or dampness of the air, by the following method:—The instrument is placed under a bell-jar, the air of which is dried by chloride of calcium, and when the needle stops at a fixed position, it is marked 0°; the apparatus is then placed under another bell-jar, the interior of which is moistened with water: the air contained in this jar is thus saturated with vapour. The needle passes in the contrary direction, and ends by stopping at a point which corresponds to the state of the air saturated with vapour.

This point is marked 100°, and the interval comprised between the two fixed points is divided into 100 equal parts or degrees.

The hygrometer thus constructed and graduated shows well if the air is more or less damp; but, to conclude, from a marked hygrometric degree, the tension of the vapour with regard to the tension of the air, saturated at the same temperature, one must construct and calculate empirical tables which give this relation. A thermometer is generally added to a hair hygrometer, the utility of which will be understood after what we have just said. Hair hygrometers present this inconvenience, that their indications are not exactly comparable; hairs belonging to different individuals have not in the same degree the property of absorbing dampness.

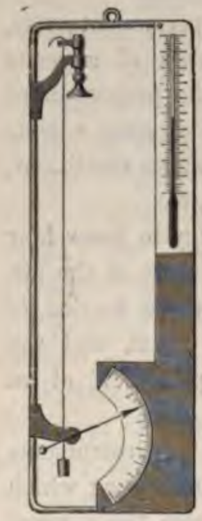


FIG. 449.—De Saussure's hair hygrometer.

The hygrometric state of the air can also be deduced from the temperature to which it must be lowered, in order that the vapour which it retains may be sufficient to saturate it. The instruments which serve to determine this temperature are condensing hygrometers, thus named because the vapour condensed on the surface of a polished metal indicates the saturation of the air produced by an artificial falling of the temperature: these instruments are prepared by meteorologists on account of their precision. The quantity of atmospheric aqueous vapour generally increases with the tempera-

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ture; it is greater at sea and on the coast than far inland. It varies according to the hours of the day, increasing in proportion as the temperature rises. It also varies in the various seasons of the year; the warmest are those in which the air contains the greatest absolute quantity of vapour. The contrary, however, happens for relative dampness; it is generally during the night, or during the cold season, that it exists in greatest quantity,—that is to say, that the air is nearest saturation. Lastly, the direction of the wind has also a great influence on the hygrometric condition of the air, but it is impossible to give an idea of this influence without entering into extremely complex details, since the atmospheric conditions change, so to speak, in different regions of the globe.

Dew is nothing more than a deposition of the vapour contained in the air, which the cooling of objects situated on the surface of the ground has condensed into fine drops during the night. Dew appears especially during the serene nights of autumn and spring: because, at these periods, there is a great difference between the warm temperature of the day and that of the night. The atmosphere then contains, during the day, a sufficient quantity of vapour; and, if the sky is not covered with clouds, the ground radiates into space a quantity of heat, without the air in itself being cooled as much in its upper strata: but the contact of the ground will cause the temperature of the lower strata to fall, which will be saturated, and their vapour will be deposited in the form of dew on bodies, with much more abundance as these are less good conductors of heat, and endowed with greater radiating power.

Clouds prevent radiation from being so intense; and, moreover, between them and the ground an exchange of heat takes place: this explains why there is little or no dew in dull weather.

When the temperature of the night falls below zero, the dew deposited on the ground is congealed, crystallizing in the form of very fine icicles: this phenomenon is known as *white* or *hoar frost*.

When the condensation of the atmospheric vapour is determined by a fall of temperature in the upper strata of air, very small drops of water produced by this condensation, collected in a space more or less great, interfere with the transparency of the air, and form either clouds or fogs. Fogs only differ from clouds by their proximity to the ground.

Clouds continually change in form; but it is not alone the influence of aërial currents which modify them: sometimes they are dissipated, because they meet with strata of a higher temperature, and part of the water which forms them passes into the state of vapour; sometimes, on the other hand, they increase by a fresh condensation, and then, if the drops assume a more considerable volume and weight, they fall to the ground, presenting the phenomenon of rain. A change of wind often brings rain, either because the cold masses of air are thus mixed with air charged with vapours, and saturate them, or, on the other hand, because the masses of warm air charged with vapour are then mixed with a colder atmosphere.

In winter, when the temperature is low enough for the drops of water, forming clouds, to be congealed, snow falls instead of rain. Snow-flakes are formed by the agglomeration of small crystals, deposited in a star-like form, with a symmetry which is really wonderful. We have reproduced in Fig. 450 the various forms which the navigator Scoresby has described, and figured in the account of his voyages to the Arctic seas. It has been remarked that the greatest number of them are hexagonal polygons—stars with six points: all the small facets forming the crystals making angles of 60° or 120°. Sometimes drops of water from the clouds are agglomerated, on congealing, into little irregular masses more compact than snow. They then fall as *sleet*, or *hail*.

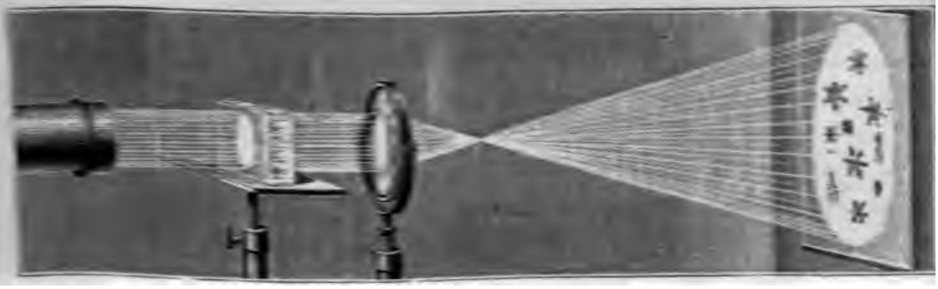

FIG. 451.—Dissection of a block of ice by the solar rays. Crystalline structure of ice.

The crystalline form assumed by atmospheric water on congealing also belongs to the compact and transparent masses of ice which the low temperatures of winter produce on the surface of ponds, lakes, and rivers. On examining ice with the naked eye, its structure appears confused, but Tyndall has succeeded in proving its crystalline texture by a very curious experiment, which consists in passing a beam of solar or electric light through a block of ice. The heat of the beam is partly absorbed by the molecules of which the block is composed, and the return to the liquid state is gradually produced.

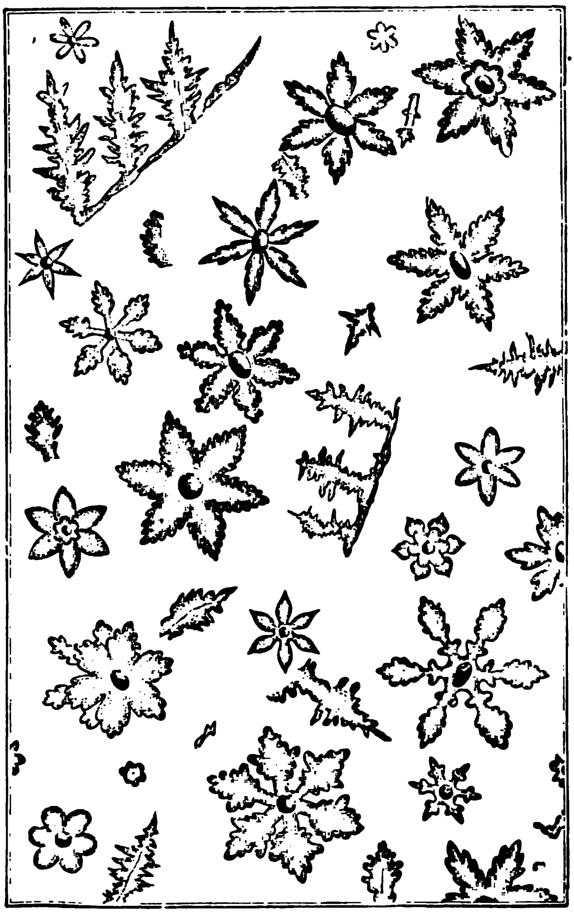

FIG. 452.—Ice-flowers (Tyndall).

By examining what is passing in the interior of the block by means of a magnifying glass, or by projecting its image on a screen by means of a lens, the work of decomposition of which we speak is rendered evident. Here and there we see star flowers with six rays, with serrated edges; at the centre of each a spot is seen presenting the lustre of burnished silver, and Tyndall has shown that this spot is a vacuum, the production of which is due to the diminution of volume undergone by the ice as it passes to the liquid condition, so that this curious phenomenon proves the contraction of water during its passage from the solid to the liquid state.

The various phenomena we have just rapidly described, and which we have placed under the common denomination of aqueous meteors, because water in its different states forms the substance of them, have for their cause the variations of temperature. This last element has therefore great importance in meteorology; moreover its influence is very great on organized and living beings, both animal and vegetable, on their production and development,—in a word, on the life on the surface of the globe; it acts in such a continuous manner on the health of man and his auxiliaries, that the problem which consists in determining its variations, periodicity, and anomalies, is surely one of the most interesting in meteorological science. But its complexity is such, that it is not possible to touch upon it here or even to glance at it; we shall content ourselves with describing the instruments used in the observation of the temperature of the air. We already know the nature of the different kinds of thermometers used to this end: it only remains for us to speak of the form given to them, when we desire to know the highest or lowest temperature which the air has attained during a certain interval of time. These are termed *maximum and minimum thermometers.*

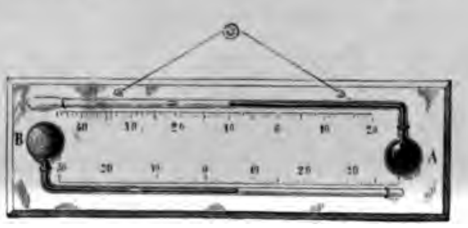

Fig. 453.—Rutherford's maximum and minimum thermometers.

Fig. 453 represents an instrument of this kind invented by Rutherford; it consists of two thermometers, one of mercury and the other of alcohol, placed horizontally on a wooden frame. In the interior of the first tube, a little cylinder of steel or enamel is in contact with the surface of the mercury, which the liquid forces before it as long as the temperature rises; but which it leaves in its place, at the most distant point of its course, when the temperature falls. The end nearest the mercury evidently indicates the maximum temperature. In the tube of the alcohol thermometer is an enamel cylinder which the alcohol moistens and leaves in its place when the temperature rises, and which it draws with it when it falls. The minimum is then given by the end of the cylinder furthest away from the reservoir. When the instrument is adjusted for an observation, care must be taken to bring the two indices to the extremities of each liquid column; one is in contact with the mercury, and the other is immersed in the alcohol, the end most distant from the reservoir being on a level with the surface of the liquid.

To observe maximum and minimum temperatures at great depths, in the sea, or lakes, or Artesian wells, upright thermometers are used, among which we may describe those of M. Walferdin.

The maximum thermometer is constructed like a common mercurial thermometer; but the extremity of the tube is brought to a point, and connected with a lateral reservoir which contains a certain quantity of mercury. When an observation is to be made, the reservoir is heated until the mercury entirely fills the tube, then the instrument is reversed, the reservoir being uppermost; the mercury in the lateral reservoir is now on a level with the point, and on cooling to a lower temperature than that of the maximum to be determined, the tube remains always filled with mercury. The instrument, thus prepared, is placed in the medium to be observed. As long as the temperature rises, the mercury flows into the reservoir, and at the moment of the maximum the tube will be still filled. The instrument being removed from the medium and reversed, the maximum temperature will be found by heating the thermometer in water until the column of mercury is again on a level with the passage leading into the lateral reservoir.

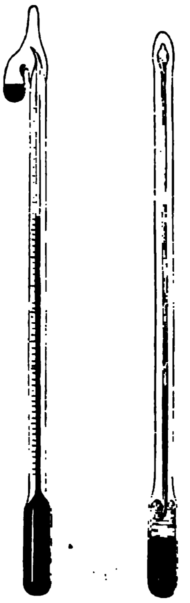

FIG. 454.—Maximum and minimum thermometers of M. Walferdin.

For meteorological observation, self-registering thermometers are now constructed which mark all variations of the temperature by means of photography, the exact time of observation being determined by interruptions of the record at known intervals.

The variations of atmospheric pressure are not less valuable to the knowledge of meteorological laws than those of temperature; we will say a few words on this subject before describing electrical and magnetical meteors.

In Chapter VIII. of Book I. we have seen how barometers show, by variations in the level of a column of mercury, the corresponding variations of the pressure of the atmosphere. These oscillations of the barometric column have very complex accidental causes. If the atmospheric column which rests upon any certain surface were always at rest, the pressure would only depend on the weight of air of which this column is composed, to which must be added the pressure resulting from the elasticity of the vapour which is mixed with it; but this state of equilibrium never exists on any part of the globe. The reasons for it are easily understood, and, moreover, proceed more or less directly from the same cause; namely, the action of solar heat.

The sun warms the surface of the ground and the strata of superposed air in any place very unequally, according to the hour of the day and the time of the year. The more considerable this heating action is, the more is the air expanded, and the more readily does it rise by diminution of density. But as, at the same instant, the regions more or less distant from the first are in different conditions, there ceases to be equilibrium: then the highest strata of air pass from the warmest region towards the coldest, and a movement in a contrary direction takes place below,—that is, a passing of the denser and colder strata of air towards the warm region. This transport of masses of air from one place to another is the cause of winds. Now, it is clear that at the commencement of this movement a diminution in the barometric pressure will be produced when the air has been expanded by the elevation of temperature; then also an augmentation will result when the temperature is lower, the weight of the air being increased by the whole weight of the strata which are spread out on the upper surface of the atmosphere. But it must not be forgotten that the heating action of the sun produces at the same time a contrary effect. The vapour contained in the air increases its elasticity as the temperature rises, so that if the barometric column falls when the density of the air diminishes, at the same time it rises under the influence of the increase of tension of the aqueous vapour. The difference of these two contrary movements produces the barometric variation.

Lastly, it is probable that atmospheric currents act in another manner on the column of mercury of the barometer. For instance, if an aërial current is propagated from above downwards, its influence will depend not only on its weight, but also on the velocity with which the gaseous mass will be moved, just as if, as M. Marié-Davy has well said, the winds have for their original cause a difference of pressure occasioned by the inequalities of temperature; they react on themselves, producing variations of pressure. It has been noticed that, at the same place, the barometric column undergoes diurnal oscillations and variations which follow the seasons of the year: both are subjected to a periodicity which agrees with the preceding explanations. But this same height is subjected to irregular variations, the causes of which are extremely complex.

Thus, the barometer rises or falls according to the direction of the prevailing wind. At Paris and over a great portion of Europe, the barometric pressure is generally higher with the north, north-east, and east wind than with the south, south-east, or south-west wind. In the southern hemisphere, the contrary takes place.

We will conclude this explanation of the causes which produce the principal atmospheric phenomena, by a short description of electrical and magnetical meteors.

In 1735, Gray pointed out the analogy which exists between lightning and the noise of thunder during storms, and the spark and sharp sound produced by an electrical discharge. But it is to Franklin that the honour belongs of having established by decisive experiments the identity of the causes of these two phenomena. In 1749, this illustrious physicist, after having noticed all the similarities between thunder and electricity, which had been hinted preceding observers, conceived the possibility of utilizing the power of points to preserve edifices from lightning. At the same time he gave all the indications necessary for detecting by experiment the electrization of thunder-clouds. Three years later, he used a kite surmounted by a metallic point to draw sparks from the string wetted by the rain. Nearly at the same time Dalibard realized in his celebrated experiment at Marly-la-Ville, the conditions which Franklin had proposed, and De Romas raised an electrical kite at Nérac. During a slight storm, this last observer was able to draw sparks 4 metres (13 feet) in length from the extremity of a cord, by means of a discharger; the explosions might be compared to those of fire-arms.

Lastly, De Saussure discovered by an electroscope surmounted by a metallic rod, that thunder-clouds are electrified sometimes positively and sometimes negatively. When two clouds charged with contrary electricities come together, the violent combination of the two electricities gives rise to the production of a spark, which is *lightning*. If the discharge takes place between a cloud and the earth, the same luminous phenomenon is seen; but then the thunder is said to fall, and the lightning is called a *thunderbolt*.

The form of lightning is sometimes that of a sinuous curve, and sometimes that of a zigzag rectilinear line; at other times it does not take any precise and determined form, and only produces a confused glimmer illuminating that portion of the sky in which it appears, but the last appearance is probably owing to the interposition of clouds which hide the actual flash from the observer. There is also *ball lightning*, which moves like a globe of fire through the atmosphere, with much less velocity than that of other kinds of lightning. It often happens that the electric flash of thunder-clouds is divided into several branches, forming what is called *forked lightning*.

The colour of the light of lightning is usually white, sometimes purplish or violet, or greenish.

Sir Charles Wheatstone has measured, by a veryingenious method, the mean duration of a flash of lightning. He used a wheel having a great number of flat silver spokes, which was turned with great rapidity on its axis; the wheel being suddenly illuminated during its rotation by a light with an appreciable duration, for instance $\frac{1}{10}$ of a second: each spoke being displaced during that time will appear thickened on account of the persistence of the luminous impressions on the retina; the matter of the wheel will appear more or less continuous. The same thing takes place with a carriage-wheel which rapidly passes before us. Now, Wheatstone greatly increased the rapidity of the rotation, and always, when the lightning illuminated the wheel, it seemed immoveable, and the spokes remained distinct to the sight and at rest. He concluded from numerous experiments that lightning does not last so much as a thousandth part of a second.

The violence of the discharge which is effected between two thunder-clouds gives rise to the noise which we know under the name of *thunder*. It must be remarked that the explosion is much sharper and more brilliant the nearer the lightning is to the observer, but in almost every case the detonation is accompanied by a prolonged roll. The cause of this persistence of the noise of the discharge is due probably to two causes: first, it has been proved that a flash of lightning is often many kilometres in length, and one of the two extremities may be nearer the person who listens than the other; and although the sound is produced at the same instant in the whole length of the flash, as it takes one second to travel 340 metres, many seconds will be required for a distance of 10 kilometres. Moreover the sound reflected from the clouds and the ground, gives rise to echoes more or less prolonged. The zigzag form of lightning also explains how it is that the roll of thunder does not die away gradually, and that during its duration it is heard louder at different times.

The effects of thunderbolts present a perfect analogy with those produced by electrical discharges in machines and batteries; only they are infinitely more intense, as we may well imagine from the prodigious grandeur of the scale on which Nature works. They have been seen to overturn and carry to a distance considerable masses, such as walls and masses of rock; to melt and volatilize metals, to pierce holes through sand, which is then found vitrified and forms a kind of tube known as a *fulgurite*. This last and singular phenomenon has been produced by the help of the great battery of the Conservatoire des Arts et Métiers, and tubes have been obtained similar to fulgurites by passing a discharge through a bed formed of sand mixed with salt.

We have said above that lightning sometimes reverses the poles of the magnetic needles in compasses, or completely demagnetizes them: at other times, it produces a contrary phenomenon and magnetizes pieces of steel which it strikes.

Its physiological effects are not less curious; unfortunately they are sometimes terrible. Men and animals struck with lightning are often killed on the spot. There are one or two examples in which the shock produced by it has cured persons afflicted with paralysis and rheumatism.

Thunder-clouds, when they pass over objects situated on the ground, electrify them by induction. Such is the cause of the luminous tufts which are sometimes seen at the summits of pointed edifices, masts and ships' yards. These faint lights the ancients regarded as warnings, and sailors now call *Saint Elmo's fires;* they are explained by the considerable electric tension which conductors have when terminated in a point.

When we describe the lightning-conductor in the work which will follow this volume, we shall give details of the course followed by lightning and the means of preservation from its terrible influence.

We have already mentioned the magnificent phenomenon known as the polar aurora, which is seen in all its beauty in the northern and southern regions of our globe. It is now no longer a matter of doubt that there exists a relationship between this luminous phenomenon and terrestrial magnetism; that is, between the production of the aurora borealis and the variations of the electric currents which intersect the earth. Arago established, by exact observations, the coincidence of certain perturbations of the magnetic needle with the appearance of auroræ. These agitations commence many hours before the appearance of the light, and they are more and more intense during its continuance. A magnificent experiment of M. de la Rive has placed beyond doubt the electrical or magnetic nature of the aurora.

The auroræ boreales are visible in our climate, but they are rare and of short duration. "In the north," says M. Charles Martins, "the phenomenon is seen with such a brilliancy and magnificence that nothing can be compared to it. Bright and varied like fire-works, this spectacle changes every instant. The painter has not time to seize the forms and tints of these fugitive lights; the poet must give up describing them. Never does one aurora borealis resemble another; they vary infinitely." (*Du Spitzberg au Sahara.*)

The aurora borealis reproduced in Plate IX. from the beautiful plates in the *Voyage au Spitzberg et en Laponie*, the observation and description of which are due to M. Lottin, will give some idea of the magnificence of the phenomenon. The following is also a description which we have borrowed from M. Charles Martins, one of the *savants* who, with M. Bravais, Lottin, &c., composed the scientific commission of the expedition:—

"Sometimes the auroræ are simple diffused lights or luminous sheets; sometimes agitated rays of a brilliant white, which pass over the whole firmament, starting from the horizon as if an invisible pencil passed over the celestial vault; sometimes it is at rest; the unfinished rays do not reach the zenith, but the aurora is continued at another point; a cluster of rays starts out, spreading fan-like, then gets fainter and disappears. At other times long golden draperies float over the head of the spectator, folding over each other in a thousand ways, and undulate as if the wind agitated them. In appearance they are slightly raised in the atmosphere, and one was astonished not to hear the folding of the sheets which glided one over the other. Most often, a luminous arc is spread towards the north; one black segment separates it from the horizon, and contrasts by its deep colour with the arc of brilliant white or red which darts out its rays, is extended, divided, and soon represents a luminous fan which fills the northern sky, rises gradually towards the zenith, where its rays, on uniting, form a crown which, in its turn, darts luminous jets in every direction. Then the sky appears a cupola of fire; blue, green, yellow, red, and white, join in the palpitating rays of the aurora. But this brilliant spectacle only lasts a few seconds. The crown just ceases to send out its luminous jets, then by degrees fades away: a diffused light fills the sky; here and there, some luminous patches, similar to light clouds, spread themselves and contract with wonderful activity, like a heart which palpitates. Soon they in their turn fade: all is confused and is effaced; the aurora seems to be in its agony: the stars,

which its light obscured, shine with a fresh brig
polar night, dark and profound, again reigns i
snowy solitudes of the earth and ocean."

Bravais—in discussing the forms of a great n
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year; they contribute with the brightness of th
to destroy the sadness and monotony of Nature
in those inhospitable regions.

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